Benchmarking and Control Indicators for Electrical Substation Projects

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ABSTRACT

It is estimated that over the next two decades nearly $880 billion will be spent to build and upgrade high-voltage and distribution electrical facilities, such as substations and power lines. A major contributor to this cost can be attributed to the industry's large construction labor component, which can account for more than half of total expenditures. One way to improve labor cost efficiency is by establishing productivity benchmarking and control indicators for project performance. However, despite the size of this industry, there is general lack of published literature regarding labor control mechanisms in relation to constructing substation and transmission line projects.

This paper establishes typical benchmark indicators by using comprehensive data tracked daily or weekly for 14 well-executed high-voltage electrical substation projects. The input data collected was limited to projects completed for owner in the upper Midwest by two different construction contractors. The data analysis from these inputs yielded initial manpower loading curves and S-curves trends for the typical labor associated with above-grade substation construction. In addition, the paper provides a percent breakdown of the typical labor hours per above-grade activity. The paper also provides practitioners with practical input for managing substation construction projects by providing examples of Work Breakdown Structure, timesheets, and productivity tracking. The typical benchmarking and control indicators presented in this paper are expected to aid substation practitioners better plan and track labor performance, and also provide a framework for future research into benchmarking and control indicators in this industry sector.

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CHAPTER ONE: INTRODUCTION

1.1 Background and Introduction

As of 2015, the construction industry accounted for around $650 billion of the U.S. gross domestic product (GDP) (U.S. Bureau of Economic Analysis 2015) and employed more than 4% of the U.S. labor force (U.S. Bureau of Labor Statistics 2015). Despite its economic significance, productivity of the construction industry has been declining at a rate of −0.5% per year since the 1960s. Moreover, only about 30-40% of work on a typical construction project is considered productive, resulting in the frequent failure of delivering construction projects on time and on budget (Hanna 2010). Since this issue is most relevant to labor-intensive trades like electrical contracting, it is essential to establish productivity benchmarking and control indicators for electrical work.

There are several construction industries that already have started to gather benchmark indicators to help improve project performance. These include the electrical and mechanical building industries research done by Hanna (Hanna et al. 2002) along with transportation industry research done by WISDOT (CMCS 2012). However, while labor productivity and control indicators in the electrical construction industry has been studied closely over the last two decades, there is a general lack of research dedicated specifically to the substation sector.

This paper defines benchmark indicators as control points generated by analyzing actual quantitative labor data from recently completed substation projects. In order to establish typical benchmark indicators, this paper uses comprehensive data tracked daily or weekly from 14 well-executed[1] high-voltage electrical substation projects. The goal of this research is to therefore establish initial labor hour control indicators for high-voltage substation construction projects thru the use of benchmarking tools, and provide a framework for future research and data analysis within this industry.

1.2 Definitions

Prior to discussing the research goals and objectives, key terms for substation projects and general construction industry terms that will be referenced within this research paper will be discussed. The next few paragraphs will discuss the overall electrical grid, function of an electrical substation facility, types of electrical components within a substation, and key construction industry terms associated with labor tracking and production tools. These include key definitions such as benchmarking, manpower loading, and S-curves. Along with the definitions below, further definitions are provided in Appendix B-Glossary.

Electrical Substation

Electrical substation construction facilities are main components and destination points of electricity in the electrical grid. Figure 1.1 below shows the overall electrical grid layout, from generation, to transmission lines, to high-voltage substations, and finally to customer

[1] See Chapter 1.5 for definition of "well-executed" projects.

homes (distribution voltages). The substation facility is circled in red, and is the component within the electrical grid that this research is being completed for. The main function of a high-voltage substation facility is to change the voltage type that is received or sent out on the transmission line, or to serve as a switching station to add more flexibility on the electrical grid. (University of Wisconsin – Madison 2014)

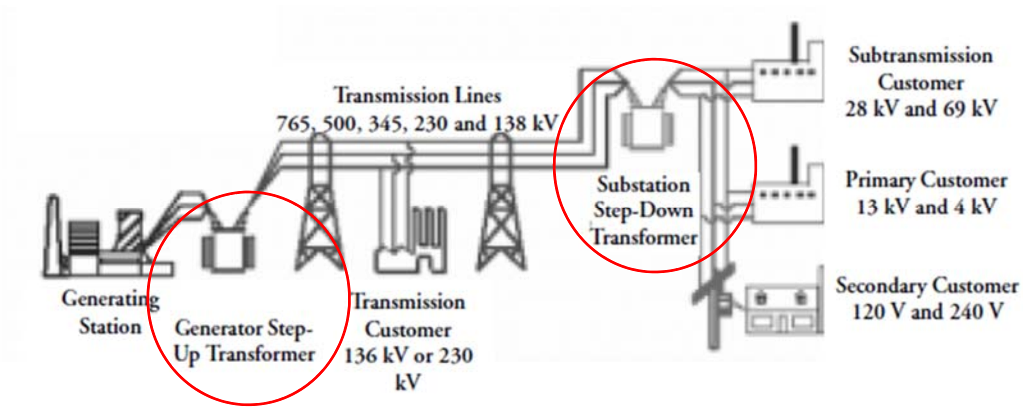

Figure 1.1 - Key Components of the Electric Power Grid (NCEP 2004)

There are three (3) main types of substation facilities installed within the electrical grid, each serving a different purpose and or function. These include the Step-Down Substation, Switchyard Substation, and Distribution Step-Down Substation.[2] These different substation types are achieved by arranging electrical components in different configurations to improve the flexibility and reliability of the electrical grid. (USDA 2001)

Electrical components or major electrical equipment include items such as power transformers for step-down substations, circuit breakers for breaking and isolating

[2] See Appendix B-Glossary for definitions of main substation facility types.

voltages, disconnect switches for visual open, and buswork for carrying the electrical current.[3] Figure 1.2 below shows the overall site layout of a substation facility with the above-grade components identified. Along with these items, substations can typically be identified as a fenced in area containing gravel with various electrical equipment, steel supports, and other metal/conductive elements. For the purpose of this research, only above-grade components is being explained as the research focuses solely on above-grade activities.

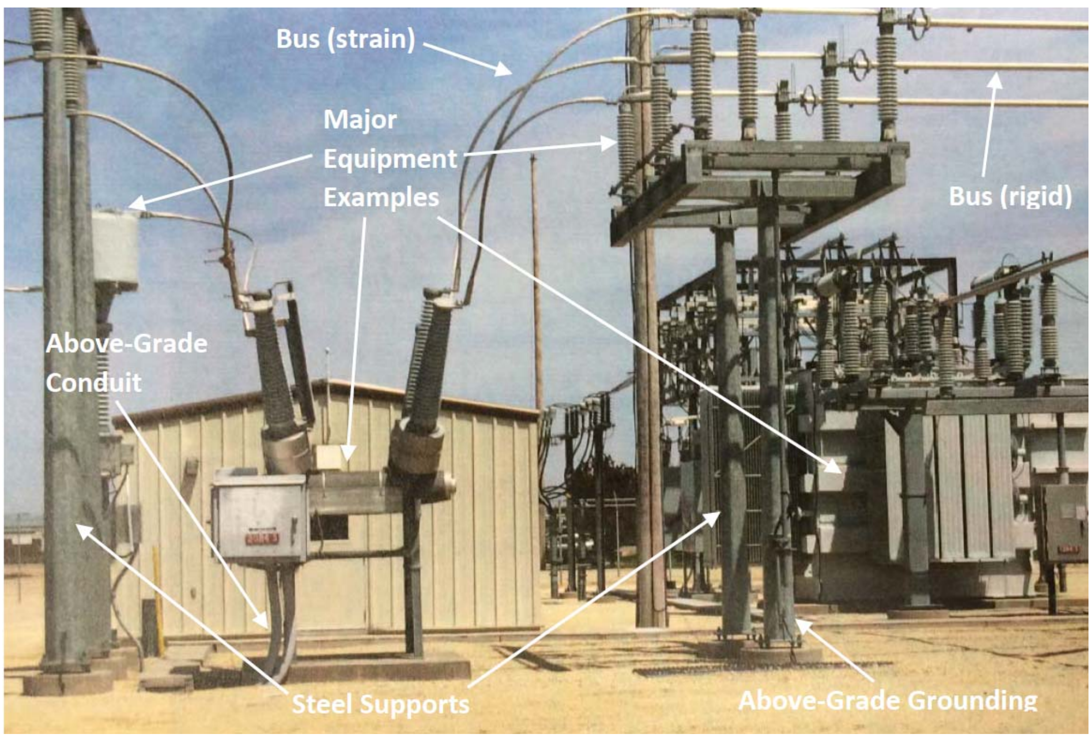

Figure 1.2 - Substation Layout with Above-grade Components Identified (University of Wisconsin-Madison 2014)

[3] See Appendix B-Glossary for definitions of above grade substation components.

Construction Industry Terms

Productivity is one of the primary methods for defining and measuring labor efficiency in the construction industry. (AACE 2011) Productivity, or production, is generally defined within the construction industry as the output of work per a measured amount of labor hours. (Shehata 2012) It can also be seen or known in the industry as a unit rate, where labor hours are described per unit of installation (Labor Hours/ Units). (Shehata 2012) Several factors that could impact labor production are crew ratio, design complexity, climate, etc.. (Shehata 2012)

Utilizing effective project labor control tools, such as benchmarking indicators, is one way project teams can have significant impacts on controlling labor hours and the overall cost performance of a project. Benchmarking indicators for controlling labor, such as manpower loading curves, standard S-curves, and other trends are defined for this paper o be established by researching actual data from "well-executed"[4] projects to identify labor trends and control points. (Hanna et al. 2002) The benchmark data can then be used as inputs or verification tools to check against estimates or actuals. (Bradshaw 2008) Benchmarking can also include research and development of standard manpower loading curves and S-curves for projects to identify project milestones and or labor control points. (Hanna 2010) Specific benchmarking tools, such as manpower loading curves and S-curves, will be further defined and discussed within the Literature review section (Chapter 2) of this paper.

[4] "Well-executed" projects defined further in Chapter 1.3 and 1.5.

1.3 Problem Statement

High-voltage substation construction projects are considered to be of high-risk, since the construction component typically accounts for 35 to 60% of the total project cost (AESO 2013). However, the current state of practice of managing substation construction lacks any kind of benchmark indicators for the labor component. Simultaneously, the high-voltage and distribution industry is projected to experience a significant amount of growth over the next two decades. This increase will involve building and upgrading power lines and substation facilities, totaling approximately $880 billion of spending (Harris Williams & Co. 2014). Therefore, there is a current need for having special benchmark indicators dedicated to substation construction projects for optimizing the labor performance.

Historical trends developed using actual project data can be used to establish effective verification tools, such as benchmark indicators (Bradshaw 2008). Utilization of benchmark indicator tools early on are important to establish a well-executed project since the ability to influence cost decreases over. Figure 1.3 below summarizes the level of influence on project cost over the life of the project, with the major influence on cost being established during the planning stage (far left of figure). Thus, to properly manage the $880 billion planned to be spend in the electrical industry, it is also important to establish dependable benchmark indicators that can be utilized early on in the project and during construction. (CMCS 2012)

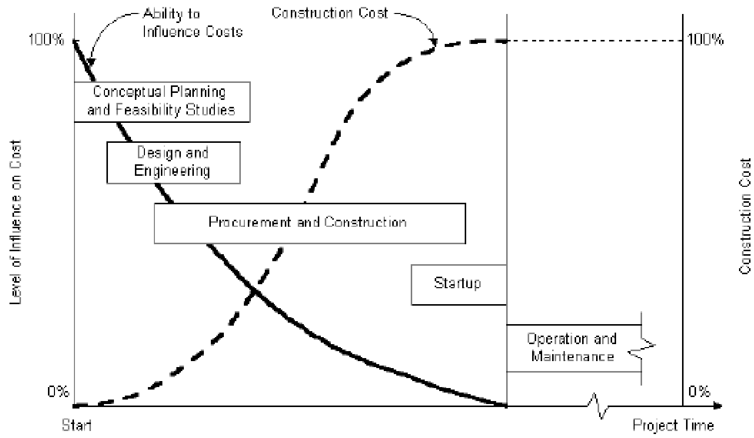

Figure 1.3 - Influence Curve for Construction Projects (CMCS 2012)

1.4 Research Objectives

This study has two primary objectives. The first objective is to use comprehensive labor hour data from actual electrical substation construction projects to establish typical labor hour control points. These include using items defined further in Chapter 2 such as S-curves, manpower loading curves, and other items like typical labor hour % per activity to establish project labor control points. The second major objective is to identify other best practices used to improve substation construction and overall project outcomes. These include items such as typical project Work Breakdown Structure (WBS)[5] and project tracking tools.

1.5 Research Scope

This study is focused on gathering qualitative labor hour data for completed high-voltage substation projects only; high-voltage defined here as voltage levels greater than 69kV

[5] Work Breakdown Structure (WBS) is a hierarchical breakdown of a project into manageable components. See Appendix B-Glossary for further definition and example.

including and up to 345kV, projects with voltages less than 69kV are not considered. Labor, material, and equipment costs (in dollars) were not gathered for the research; this was labor hour research only. The data collection and analysis process was also conducted for "well-executed" projects only. A project was considered as "well-executed" if it was identified to have the following characteristics:

0. Minimal to no change orders or requests for changes.
1. Minimal to zero safety recordable.
2. Minimal deviation in schedule duration.
3. Utilized contractor project management, tracking, and production reporting throughout construction.

Actual data was provided from upper Midwest transmission owner for projects recently completed by two different construction contractors. A total of 14 projects had labor data collected for projects of various size and scope. The average size of the projects was around 7,500 labor hours, with a range from about 1,000 - 22,000 labor hours. Substation project types included step-down (change in voltage) and switching substations. The scope of the substations included installing grass root substations (brand new facilities) and addition or expansions to existing substation sites. The voltages of the substation projects included in the study consisted of 345kV, 138kV, and 69kV. The configurations of the substations also varied, including straight bus, ring bus, and breaker and a half configurations.

As mentioned above, the scope of this study focused on above-grade activities for high-voltage substation construction only, starting typically with setting of steel and ending on above-grade scope substantial completion. Below ground activities were not included as these typically are subcontracted out to various contractors, making labor hours difficult to include and analyze consistently. The six (6) main above-grade substation activities that were included within the research include:

1. Installing above-grade ground connections to equipment, steel structures, and fencing.
2. Installing above-grade conduit, connections, and junction boxes.
3. Pulling and terminating of control cable and power cable (cable installation).
4. Setting steel supports for equipment, bus and switch supports, static masts, dead-end H-frame or A-frame assemblies, etc. (steel installation).
5. Installing major equipment such as power transformers, circuit breakers, disconnect switches, and all other minor above-grade equipment components.
6. Installing substation bus, bus connections, and hardware. This includes installation of both rigid and strain bus, jumper connections to equipment, insulators, and static shielding.

The majority of the collected projects utilized a design-assist delivery system in which the owner, contractor, and engineering were engaged throughout the process. (Hart 2007) The project contracts for projects involved were also primarily time and material (time and equipment) contract type. The contractors considered in this study were also members of major organizations such as the National Electrical Contractors Association (NECA), Occupational Safety and Hazard Administration (OSHA), and the IBEW.

1.6 Research Methodology

The process for gathering and analyzing the research data was completed in two stages. The flowchart shown in Figure 1.4 below illustrates the two stages needed to facilitate the research objectives outlined above. The first stage involved developing a survey, gathering survey results, and inputting the data. The survey was initially put into word, and was then transferred into an excel database for inputting the project data gathered. A template of the survey that was put together is attached in Appendix C. This survey can be used as a reference and template for future research within this line of study.

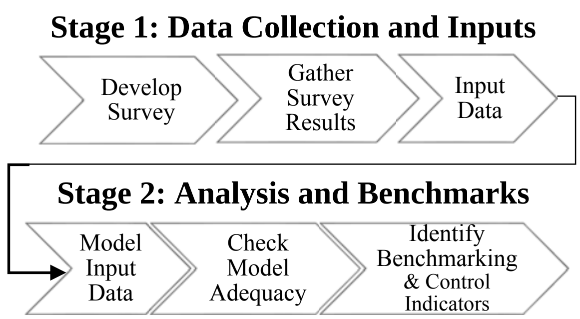

Figure 1.4 - Process for Substation Benchmark Indicator Research

The most important information in the survey to gather was contractor actual data sheets, such as actual labor hours for entire project by above-grade activity. This data was needed to generate the outcomes listed within objective 1. Additional items requested in the survey to be provided are highlighted below.

- Project information, such as type, voltage, etc.;
- Actual and planned contractor labor hours;
- Actual and planned schedule durations;
- Actual and planned peak manpower;
- Actual and planned average manpower;

- Daily and/or weekly production and time reports
- Timesheets for cost code breakout. (if available)
- Scope summary documents or construction plans

The quantitative labor data collected from the contractor sheets for several projects was also served as inputs into objective 2. Once the survey data and contractor input sheets were gathered, the next step was to consolidate the data and establish a working database. This involved inputting data such as project labor hours over the project lifecycle. This was then used to derive the independent variables "Percent Complete of Project Duration" and the dependent variables "Period of manpower as percentage of overall labor hours". For this research, a Microsoft Excel template sheet was established for inputting the data into Microsoft Excel. An example of the template used for inputting the data can be found in Appendix D.

The second stage of the research included developing model results, checking the adequacy of the model thru the use of Minitab, and establishing typical benchmarks and control indicators from the collected data. Model curves of the data were established with trend lines, regression equations, and R^2 values thru use of regression analysis. The regression plots helped determine typical S-curve and manpower loading curves for substation above-grade activities. Along with regression analysis, box-and-whisker plots were also generated at this time to help define the average percent of labor hours per major substation above-grade activity. The qualitative data was also inputted into excel for helping evaluate the trends.

The next steps in stage 2 were to review the data analysis and report out on the findings. Review of the data analysis involved initial checking the models generated for adequacy and to review the model assumptions. This involved reviewing the R^2 value closer, running residual analysis within Minitab©, and summarizing the validation of the model. The final step was to report out typical labor hour curves along with other trends and best practices that were developed throughout the typical research findings.

1.7 Research Assumptions

There were a few assumptions made during the collection and analysis of the data in the research. The main assumptions that were used are bulleted below.

1. The weeks that had low labor hours reported during holidays (such as Christmas and New Year's, and or hunting season) were typically combined together.
2. For developing the manpower loading curve trends, the data was combined and looked at on a monthly overall hours and durations.
3. Percent project time duration used on X-axis for the analysis is equivalent to physical percent complete of project. Projects are assumed to have good production as they were characterized as well-executed.
4. Design model analysis using linear regression analysis and the following model assumptions.
    a. Variables within the data is normally distributed.
    b. Constant variance of the error predicted value, i.e. equal variance.
    c. Samples are random, independent samples.

1.8 Summary

With the electrical industry forecasted to rapidly grow, there is a need for research into substation labor metrics to develop initial control indicators and to help practitioners improve project performance. Having previous research conducted in other industries, such as the mechanical and electrical building industries, sets the framework for outcomes of the research and how the benchmark indicators developed can be used to improve the overall project performance. Chapter 2 will further discuss literature review within the industry, past benchmark indicators that have been developed, and how they have been used. It will also briefly discuss the lack of labor trend research within the electrical substation industry for labor trends and need for initial research.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Literature review was done within the construction industry to determine sectors that have already begun to implement control indicators, typical benchmarking tools to utilize, and how they can be used to improve project performance. Several electronic research tools were utilized, including scholarly article search engines, past thesis documents, and other searches such as via google.

The following section will provide examples of manpower loading curves and S-curves found within other industries. The substation industry was also researched to identify the need for project benchmarks and project control best practices, but no major labor hour benchmark indicators were identified to be published in previous research.

2.2 Manpower Loading Curve: Definition, Use, and Trends in Other Industries

Manpower loading curves provide a graphical representation on how the project labor resources (in terms of labor hours or full time equivalent employees) are planned or actually being expended throughout the time of the project (duration of the project in percent of time or percent complete). (Hanna 2010) Having initial manpower curves at the beginning of the project establishes a baseline plan for the project team to monitor and evaluate as percent complete increases.

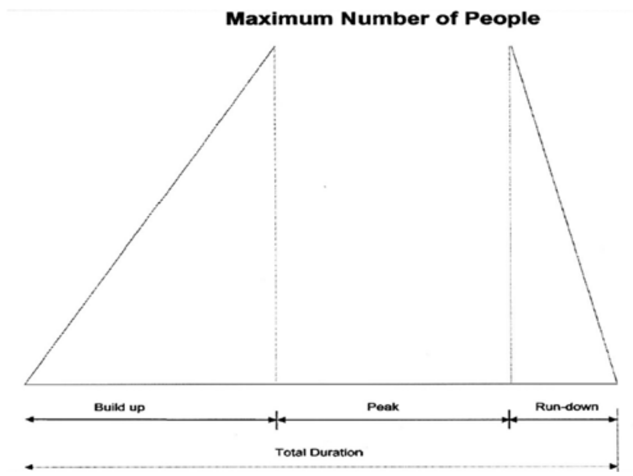

Figure 2.1 – Manpower Loading Curve Example for Planned Labor Hours (Chen 2006)

Figure 2.1 above shows a typical manpower loading curve, with the X-axis representing the duration of the project (percent time) and the Y-axis representing the number of people (or labor hours). (Chen 2006) The manpower curve above was developed using the Trapezoidal Technique (TT). The TT is a simple, yet useful tool in helping show the manpower buildup over the project, as well as show the typical cumulative resources that are needed for the project. The cumulative resources that are needed are calculated by taking the area under the trapezoidal curve. (Chen 2006) For planning purposes, this allows the project team to initially forecast labor resources, see when the project will ramp up, peak, and then run down, and provide justification for resource time and cost. (Clark 1985)

As stated earlier in the introduction, research into standardized manpower loading curves provides specific control points, such as at what percent complete the project will peak and what percent of labor hours are consumed at this point of the project. Standard manpower curves, or calibration/benchmarking curves, can be put together by researching completed projects that follow repeated work or patterns. (Clark 1985) Several other construction industries, including the electrical building, HVAC contractors, and sheet metal contractors have conducted research into manpower curves for their associated line of work. For example, Awad S. Hanna and et. al conducted research of 59 projects within the Electrical and Mechanical building contractors.

The trends of the manpower consumption for the electrical building projects researched can be seen below in Figure 2.2. The figure shows the project duration on the X-axis in terms of percentage of total time, and the Y-axis with the overall manpower as a percentage of the peak manpower vs. the average manpower of the project. This shows that on average, for the projects researched that at about 50-70% of the project duration is when the peak to average ratio is greatest at around 160% calculated using the Allen trapezoidal technique. (Hanna et al. 2002) This should be the primary timeframe of the project in which the contractor (or owner) tracks, monitors, and reacts in better detail as it is the critical time frame of the project. (Hanna et al. 2002)

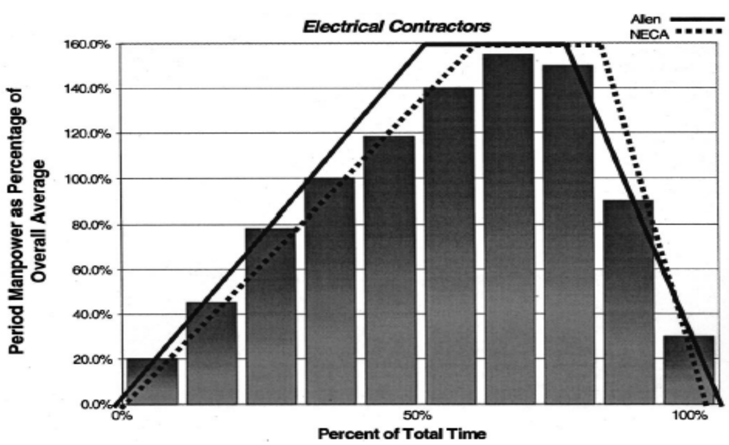

Figure 2.2 - Electrical Building Contractor Manpower Loading Ex**.** (Hanna et al. 2002)

Similar to the research above, Hanna also has developed research into the HVAC and sheet metal contractors using the trapezoidal technique. (Hanna et al. 2002) Hanna developed specific control points along the project that indicated how many labor hours typically should be consumed and at what durations for both types of projects. The data analysis showed that on average, at about 50% of the project duration around 65% of the total labor hours of the project should be consumed for sheet metal projects, and about 40% used at 50% of the time for mechanical projects. (Hanna et al 2002) Figures 2.3 and 2.4 below show the trends that were developed for sheet metal and mechanical construction respectively. These control points are important to help not only plan the project, but to help the team gauge performance as the project takes place and react more proactively to reduce cost and schedule overruns. (Hanna et al. 2002)

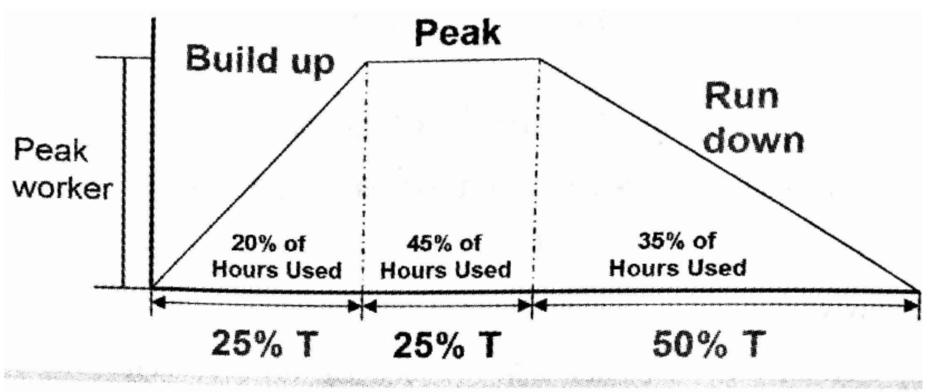

Figure 2.3 - Sheet Metal Contractor Manpower Loading Curve (Hanna et al. 2002)

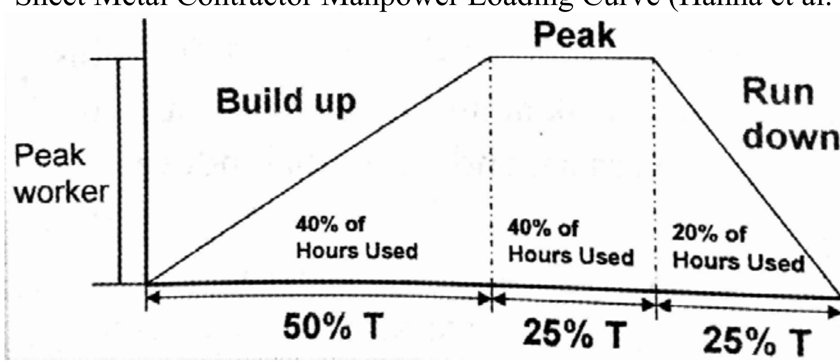

Figure 2.4 - Mechanical Contractor Manpower Loading Curve (Hanna et al. 2002)

2.3 S-Curve: Definition, Use, and Trends in Other Industries

S-curves are similar to the manpower loading curves described above in that they are also used to track planned labor over time. (Hanna et al. 2002) However, S-curves look at the data on a cumulative scale to show how the labor progresses over time. (Chen 2006) When plotted, the cumulative data over time typically resembles an “S” curve shape, hence the typical “S-curve” name used in the industry. Figure 2.5 below shows an example of a typical S-curve profile for a project with the different build-up, peak, and run-down stages. The S-curve is developed by taking the area under the curve of the TT output, and then plotting the cumulative labor hours on the Y-axis over time on the X-axis.

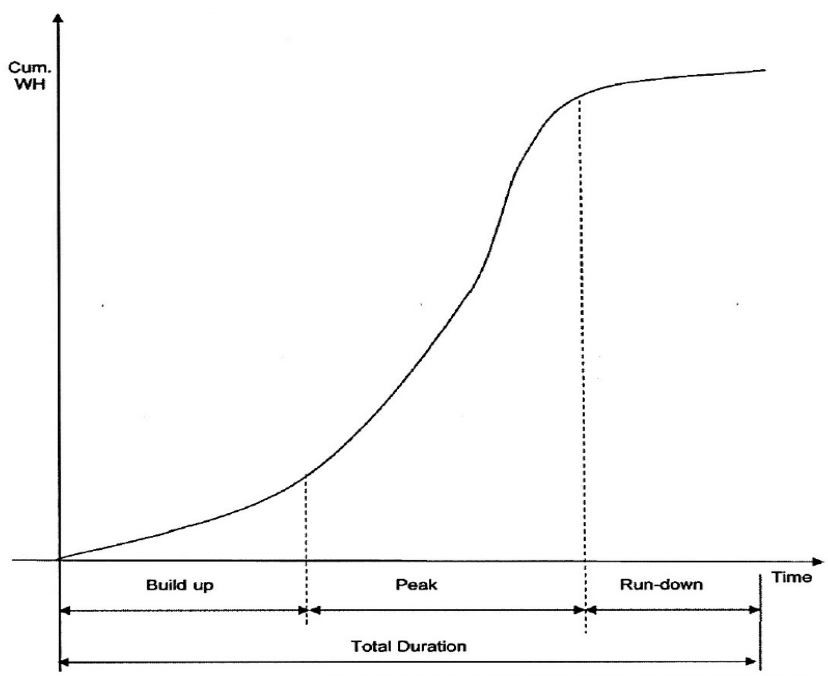

Figure 2.5 - S-Curve Example for Planned Cumulative Labor Hours (Chen 2006)

The planned S-curve can also then include actuals as the project progresses over time to identify any variances in the planned labor hours. (Hanna et.al 2010) This provides additional project controls for team members to evaluate from real time, and make informed decisions based off especially if deviations occur. (Chen 2006) Figure 2.6 below shows an example of this with the actual labor hours lagging over time when compared against the plan. This could either mean that the project is behind schedule with low production, or delayed. The project team members should use this data validation tool to then properly analyze the project performance and take any corrective action as needed. (Chen 2006)

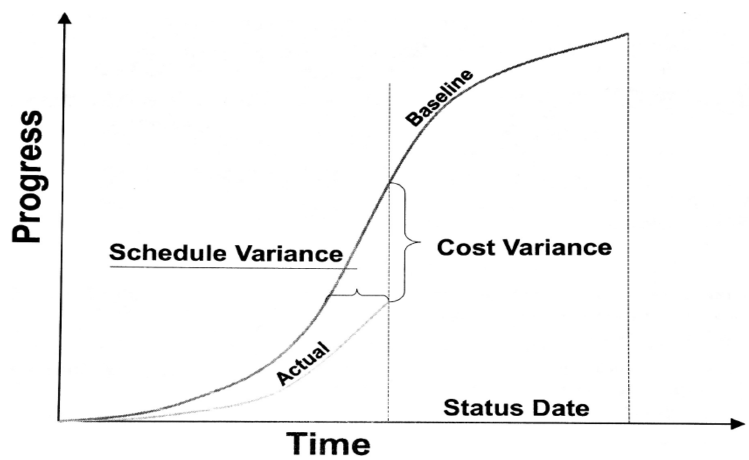

Figure 2.6 - S-Curve with Actual vs. Planned Progress
(University of Wisconsin – Madison 2012)

Additional data, such as earned value technique could be used to determine project performance, where earned value is the calculated by taking the base or estimated planned hours multiplied by the percent complete. This can be done for the entire project, or by main construction activities. (Hanna 2010) By adding the actual and earned value components to the S-curve, the project management team can find ways to mitigate losses before the project gets out of hand. (Hanna 2010)

Similar to the manpower loading curves produced above for sheet metal and electrical building contractors, Hanna also produced a typical S-curve for sheet metal contractors within the research. (Hanna 2010) Figure 2.7 below shows the typical cumulative labor hours burned for sheet metal projects, with duration in time on the X-axis and cumulative labor hours on the Y-axis. From the chart, it can be seen that at roughly 50% of the project duration, the team should have expended only roughly 65% of the projects total labor hours, which is consistent with the manpower loading trends shown earlier. This is a useful visual tool to use for not only planning a project and cross checking of an estimate, but to track actuals against for deviations as noted earlier.

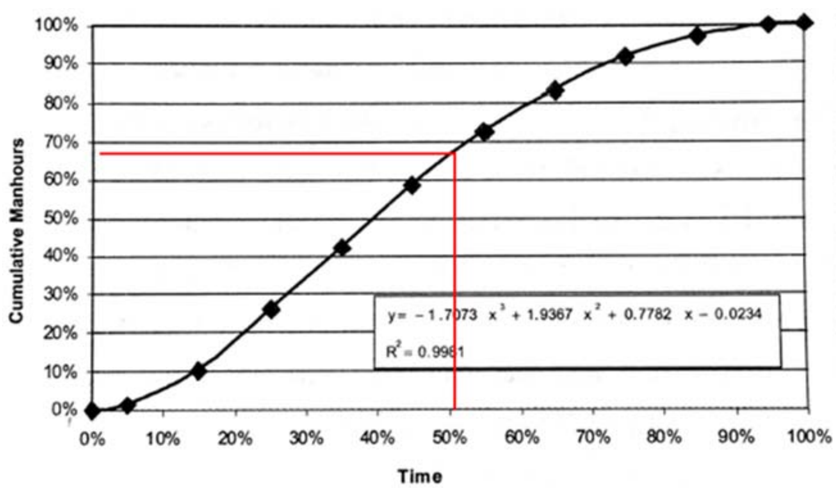

Figure 2.7 - Typical S-Curve for Sheet Metal Contractors (Hanna et. al 2010)

Research into S-curve literature also showed that the transportation industry has developed trends and control points as well. In 2012, the University of Wisconsin-Madison Construction and Materials Support Center teamed up with WIS-DOT to research over 280 transportation construction projects. (CMCS 2012) From the research, the team was able to develop a typical S-curve profile for cost instead of labor hours with a very high statistical correlation (R^2 value). The WIS-DOT research team also established a range of control points based on the standard deviations of the averages calculated. (CMCS 2012) Figure 2.8 below shows the S-curve and control points that were established from the WIS-DOT research. The figure shows a fairly linear S-curve, with about 60% of the cost being expended at around 60% of the project duration. This linear trend seems fairly accurate as transportation road projects are fairly linear in nature with how they are constructed and sequenced. (CMCS 2012)

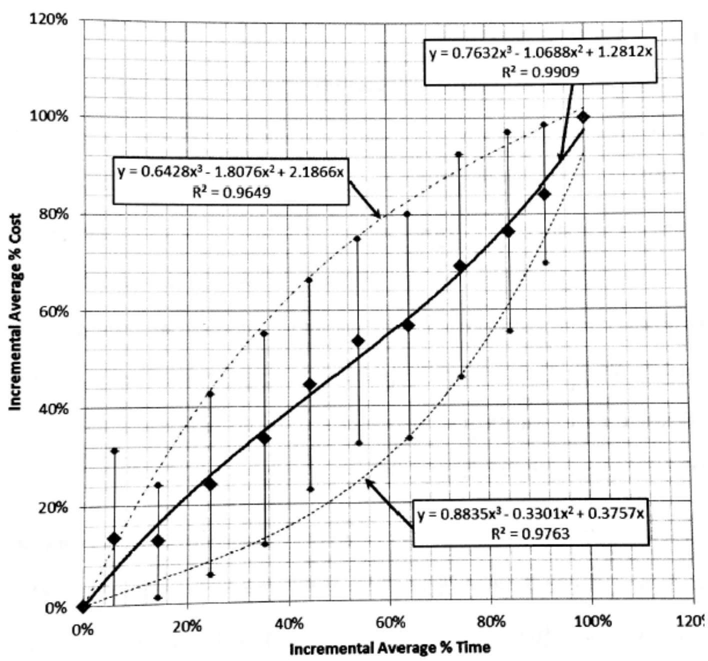

Figure 2.8 - S-Curve and Control Points Transportation Projects (CMCS 2012)

2.4 Summary

The literature review discussed above provides a framework for understanding manpower loading curves and S-curves further, and how other industries are utilizing them. Even though other industries have these benchmarks for high level trends, they still don't provide adequate correlations for substation construction sector, specifically since the activities and equipment installations are different. Research was conducted on several major scholarly article search engines, and labor hour control points could not be found for electrical substation projects. Therefore, the research being conducted in this paper will provide a missing component to the high-voltage industry and aid in establishing initial typical control indicators for substation projects and establish a framework for future research in this industry. The following chapter (Chapter 3) will discuss the characteristics of the substation projects included within this research.

CHAPTER THREE: DATA CHARACTERISTICS

3.1 Introduction

For this research, a total of 14 “well-executed” projects were gathered from an upper Midwest transmission owner for projects completed by two different construction contractors. As stated earlier, the focus of this research involved installation of substation above-grade components only. The projects had various voltage types, scope (new, expansion, size), and project labor hours. These projects were all conducted with the contractor acting as the prime contractor for the above-grade scope of work being researched. The sections below will further define the project types, voltage classes, equipment types and equipment quantity ranges, along with project labor hour ranges.

3.2 Project Types, Locations, Use, and Voltages

As mentioned above, 14 total “well-executed” electrical substation projects from the upper Midwest were used within the research analysis. The 14 projects provided a sample from two different substation contractors for substation projects with various type of substation (new or expansion), overall functionality of the substation, location, and voltage class of the project. The research included 8 new substations and 6 existing substations that were being expanded. The majority of these projects involved installing a step-down substation[6]. For example, 9 out of the 14 projects were characterized from the survey data as change in voltage substations, while the remaining 5 were switching substations.

[6] See Appendix B – Glossary for further definition of “step-down substation”. This is also commonly known as a “change in voltage” substation type.

The locations of the projects were also identified and documented, with 12 out of the 14 projects taking place in rural areas. This is fairly common in the industry for substation to be located in rural areas to help reduce aesthetical impacts to cities and other urban areas. Also, of the 14 projects, 70% of the projects considered had primary voltages of 138-69kV while the remaining projects included 345kV voltages. Figure 3.1 below summarizes the project characteristics included within the research study and Appendix E contains these in tabular format.

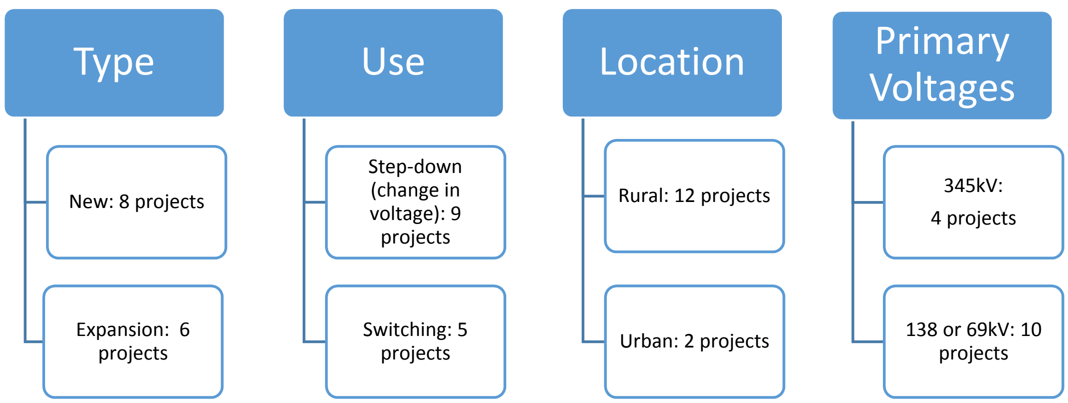

Figure 3.1 - Researched Substation Project Characteristics

3.3 Project Labor Hours

The actual labor hours ranged from 1,200-22,000 labor hours, with an average of approximately 7,500 labor hours. Figure 3.2 below illustrates the various sizes of the projects in terms of labor hour ranges on the X-axis (in terms of 1000 labor hours) vs. the frequency of the labor hour ranges on the Y-axis. From the figure below, it can be seen that the majority of the projects had less than 10,000 actual labor hours. This is important to consider when reviewing future projects against the results generated within this research for consistency.

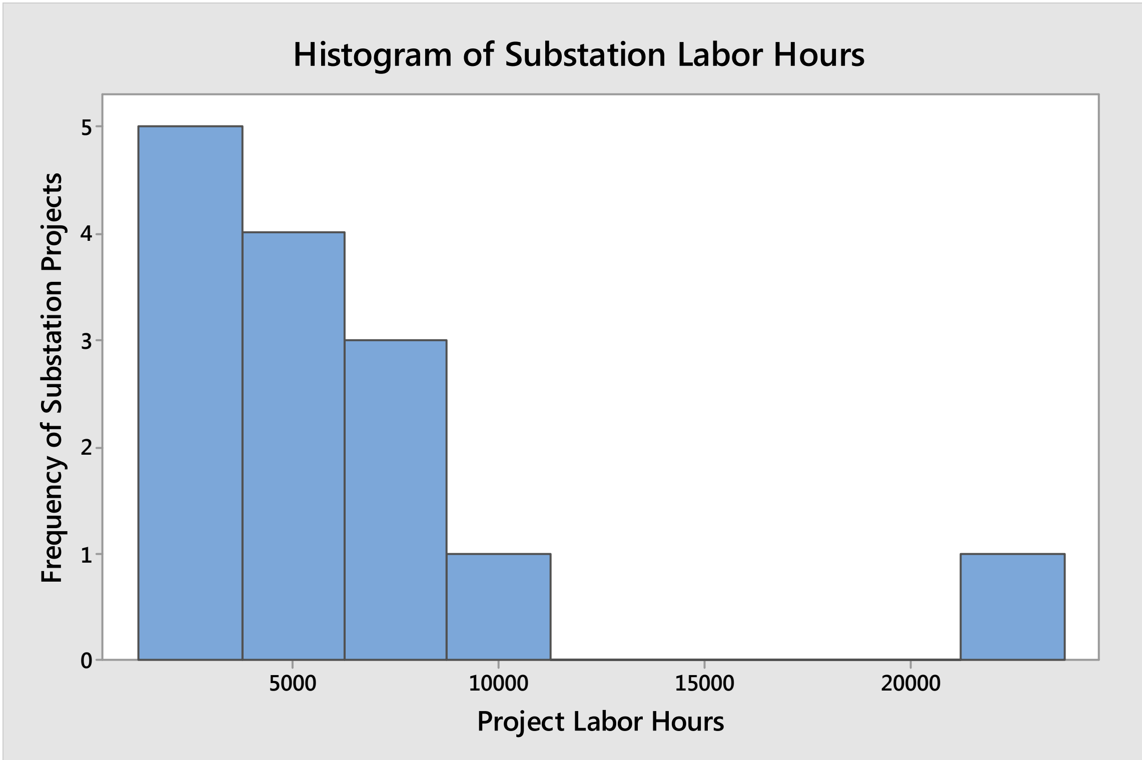

Figure 3.2 - Histogram Distribution of Substation Projects Researched by Labor Hours

3.4 Project Equipment Quantities

Along with the varying labor hours, the substation projects also had varying quantities of equipment installations, with the major equipment quantities gathered being circuit breakers and power transformers. From the survey data inputs, all project types included installation of circuit breakers ranging from quantity of 3 to 17 depending on the project scope. For a new, 69 or 138kV substation, the average quantity of circuit breakers installed was around 9 circuit breakers per project. This varied depending on the function of the substation, and whether or not it was being installed to serve as a switching substation (which typically have more circuit breakers) or a change in voltage substation. Figure 3.3 below shows the various quantities of circuit breakers of the projects in terms of quantity of circuit breakers on the X-axis (Each) vs. the frequency of the number of projects that had that range of circuit breakers on the Y-axis. From this, it can be seen that the majority of the substation projects had 4-10 circuit breakers.

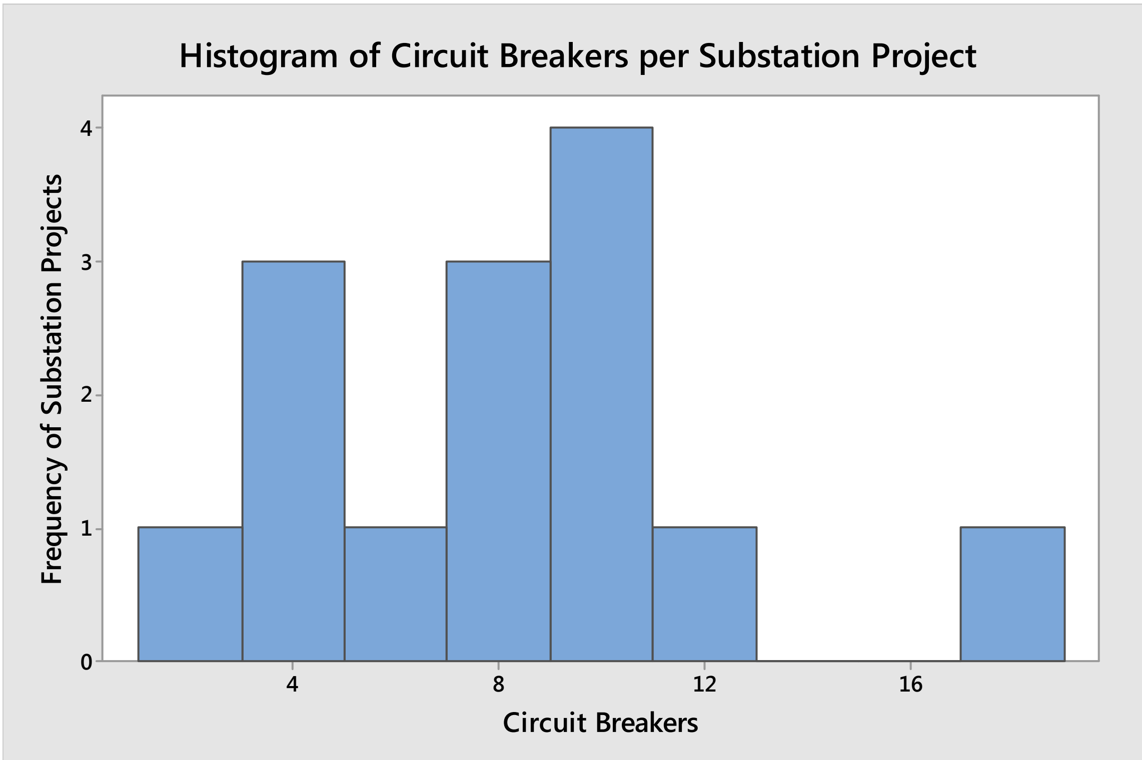

Figure 3.3 - Histogram Distribution of Substation Projects Included by Circuit Breaker

The number of voltage transformers were also requested within the survey and documented for research analysis. The range of number of transformers on the projects ranged from 0 (primarily for switching substations) to 2 (primarily for new 345 and 138 kV substations). Figure 3.4 below shows the distribution of transformer ranges from 0, 1, to 2 on the X-axis and frequency of the transformer quantity ranges on the Y-axis. From this, it can be seen that the sample size was fairly uniformly distributed (bell-shaped).

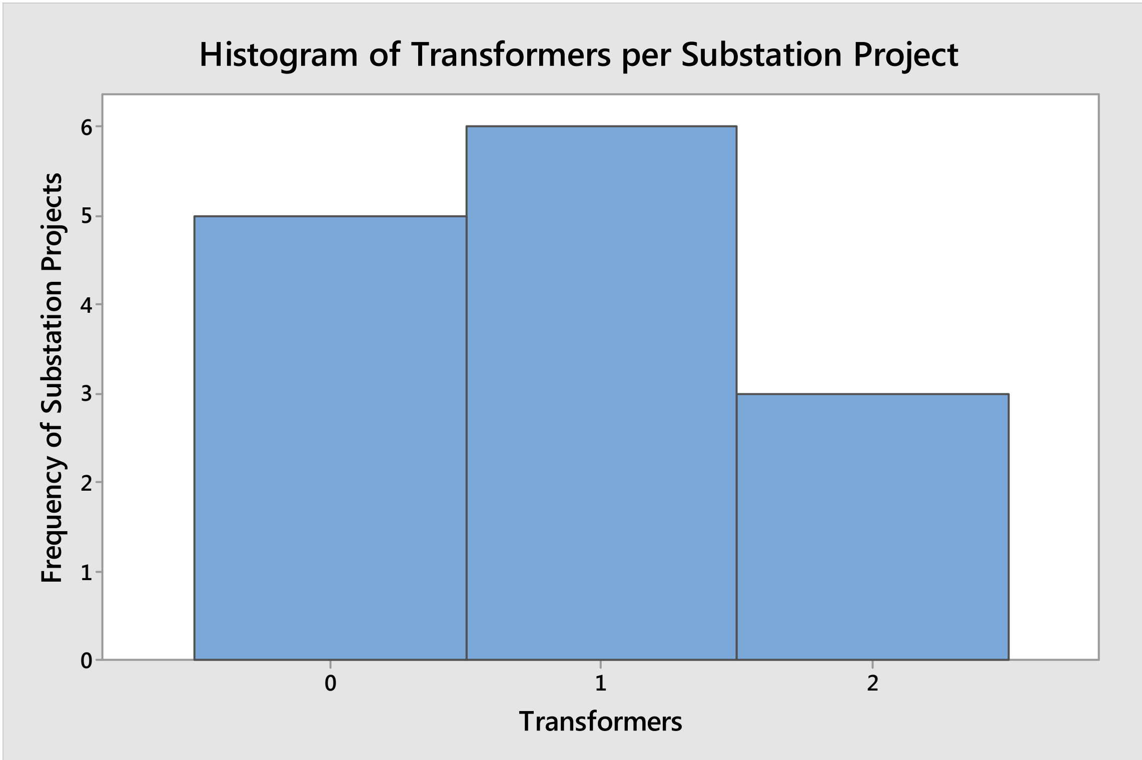

Figure 3.4 - Histogram Distribution of Substation Projects Included by Transformers

3.5 Summary

The data characteristics above were provided to describe the types and different characteristics of the substation projects researched and analyzed within this paper. During the data collection process, 14 projects from 2 different contractors in the upper Midwest were gathered, which included labor hours and major above-grade component quantities. Chapter 4 will discuss the statistical analysis and results generated from the substation data gathered above.

CHAPTER FOUR: DATA ANAYLSIS - CONTROL INDICATOR RESULTS

4.1 Introduction

After documenting the project characteristics in Chapter 3, the next step of the research was to develop typical benchmark indicators for substation labor as set out in the objectives. Tools such as manpower loading curves, S-curves, and boxplots were used to identify typical benchmark indicators. The primary method for analyzing the data involved plotting the actual labor hours and then running a regression analysis (as noted earlier in the assumptions section) for the data points.

To recap what was discussed earlier in Chapter 1 under the "Research Methodology" section, a regression analysis was used to plot a typical regression curve (or model) for the manpower over time and also to derive prediction equations for standard substation curves. These results were then used to show how well the predicted equation can be used to generate a response variable. For our models, the response variable (Y-axis) is "percent cumulative labor hours" for the S-curve and "percent of above-grade hours/average hours" for the manpower loading curves. The response variables mentioned above are dependent on the independent variable (X-axis), which for this research is "percent time" defined as the duration of time for completing the above-grade scope of work.

Along with the regression analysis, additional statistical analysis was ran in Minitab© to determine S-value, P-values, F-values, and to also check the adequacy of the regression model using residual analysis plots. Boxplots (also known as box-and-whisker plots) were completed for the average percent of labor hours by task, which will further be defined as the activity contribution factor (ACF), and schedule durations. This was done to provide a range of typical values versus reporting out a single average. The benchmark indicator results were developed either through the use of Microsoft Excel (primarily for Regression analysis) or Minitab© statistical software (for additional statistical analysis values, checking model adequacy, and box plots).

4.2 Overall Manpower Loading Curve

Manpower loading curves are used to describe the build-up of the manpower over the duration of the project. For substation manpower loading curves, snapshots at each month were taken to determine the percent time and the percent labor hours. The labor hours were taken at month-end (as noted in assumptions earlier) due to the variability in labor hours from week to week. To be consistent with other industry research, the points on the Y-axis are calculated as the actual labor hours at a specific time divided by the average labor hours for the project (shown below on the Y-axis as a percentage). This allows for a typical "peak labor hours/average labor hour" ratio (P/A) to be developed. A regression analysis was then ran on the data points to establish a typical curve, model equation, and also an R^2 value. See Figure 4.1 below for manpower regression plot.

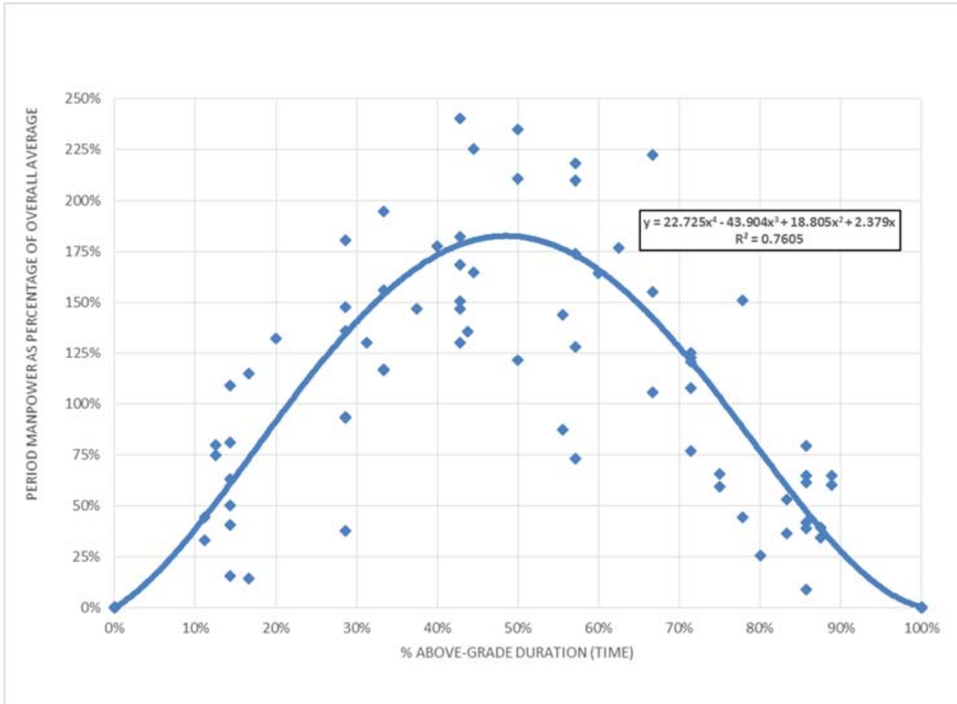

Figure 4.1 - Manpower Loading Curve for Overall Above-grade Construction

Figure 4.1 above shows the individual points that were plotted (blue dots) for the project along with the regression analysis trend line (solid blue line). From the regression analysis, the bell shaped trend shows that the labor hours typically peak around 50% with a ~180% peak to average ratio. The R^2 value, which is shown under the equation in Figure 4.1 for a fourth order polynomial, was calculated as $R^2 = 0.7605$. The higher the R^2 value, the better the model generally fits with the data set. The 0.7605 value that was calculated is consistent with similar mechanical manpower loading curves published in the mechanical and electrical building industry. (Hanna et al. 2002) This will be checked initially in section 4.3 with residual analysis.

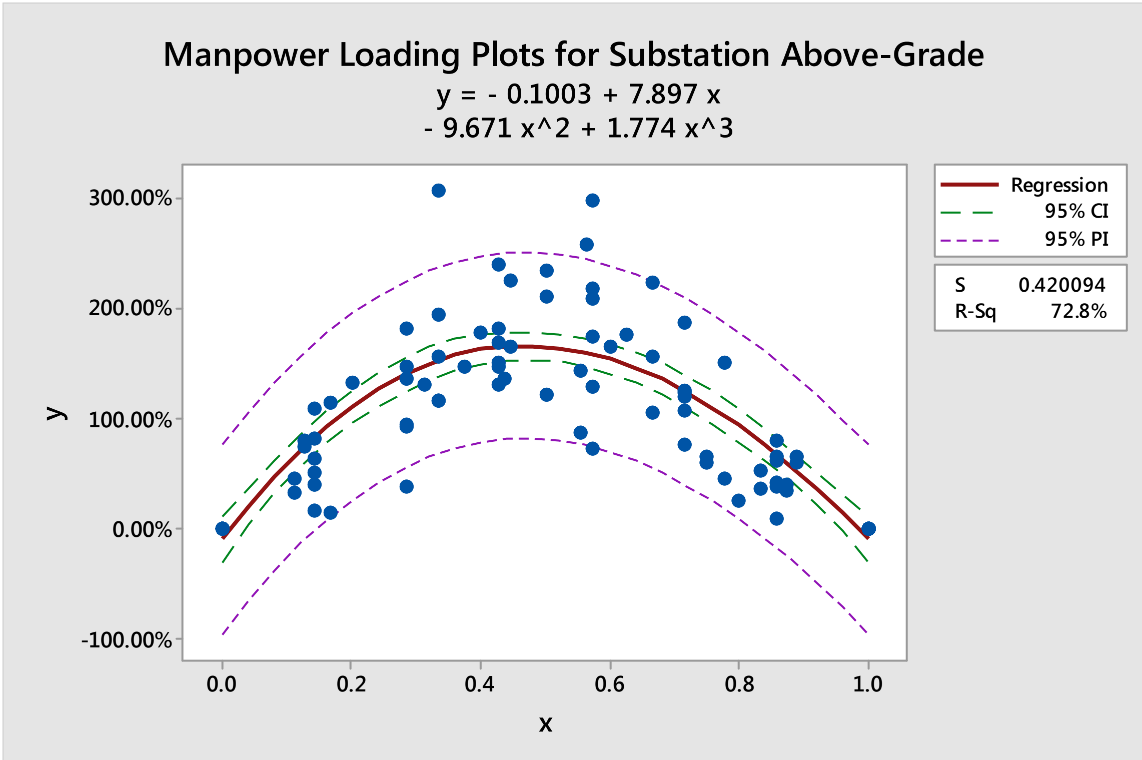

Figure 4.2 - Minitab© Regression Analysis for Overall Above-grade Construction

In addition to the Microsoft Excel analysis shown above in figure 4.1, the data points were plotted within Minitab© to confirm the manpower loading curve research findings and regression analysis. As shown in Figure 4.2, the results of the cubic regression analysis in Minitab© are consistent to the Excel fourth order analysis with a R^2 value of 0.728. Again, this R^2 value falls in line with other research. Along with model fit, dotted lines are also included to represent prediction intervals (PIs). The PI lines are provide a range of values for outputs (+/-) 5% from the typical value of interest. The results from Minitab© also include the calculated S-value which indicates the standard error of the estimate. For model fits, a smaller S-value is desired as it further indicates that the data points fit close to the fitted line. (Frost 2014) As seen above in the right hand side of Figure 4.2, the S-value for the cumulative substation manpower curve was calculated as S=0.42. From the analysis, we conclude that the model appears to be adequate for a typical, high level trend. Additional data collection and statistical analysis could be done in future research to help improve the R^2 and statistical values shown above.

Along with the bell-shaped curve, a few other important characteristics with the rate of manpower consumption can be noted thru the use of the trapezoidal technique discussed earlier in Chapter 2. This includes the overall peak to average ratio (P/A) and the main transition periods of manpower consumption; Figure 4.3 below captures these characteristics. The first characteristic is the P/A ratio. The P/A ratio for substation projects was calculated to be ~180%. This is important for planning the construction resources to be expended on a project.

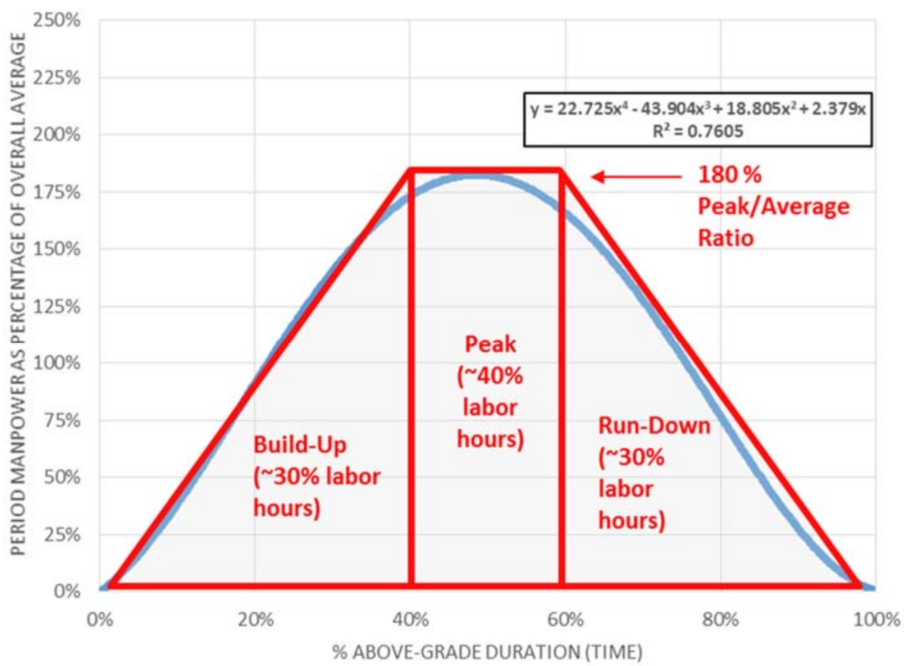

Figure 4.3 - Overall Manpower Loading Curve for Above-grade Construction

The second characteristic is that the trapezoidal technique divides the manpower loading curve into three main stages: build-up, peak, and run-down. The build-up of manpower occurs between 0% – 40% of the project duration, accounting for approximately 30% of the project labor hours. The peak stage occurs between 40 – 60% of the project duration, accounting for approximately 40% of the project labor hours. This is consistent with the industry research results presented earlier in Chapter 2 in which mechanical and electrical building researched showed 40% labor hours during peak time. During the peak stage, the project team should carefully plan, track, and monitor the labor component of the project because the bulk of labor hours is expended over a short timeframe (Hanna et al. 2002). Lastly, the run-down stage typically occurs between 60% – 100% of the project duration, accounting for the remaining 30% of the project labor hours.

4.3 Minitab© Residual Analysis for Overall Manpower Loading Curves

After plotting the manpower loading curves in excel and Minitab©, further analysis was conducted in Minitab© to run initial checks on the model curve for adequacy and to check the assumptions made earlier. This involved performing a residual analysis with plots to analyze the residuals. A residual represents how much the actual response deviates from the fitted model. (Kouiden 2012) For the analysis, a smaller residual is desired as this indicates a well fit model. Figure 4.4 below shows the residual plot analysis for the manpower loading curve presented in section 4.2. See Appendix F1 for more Minitab© report results.

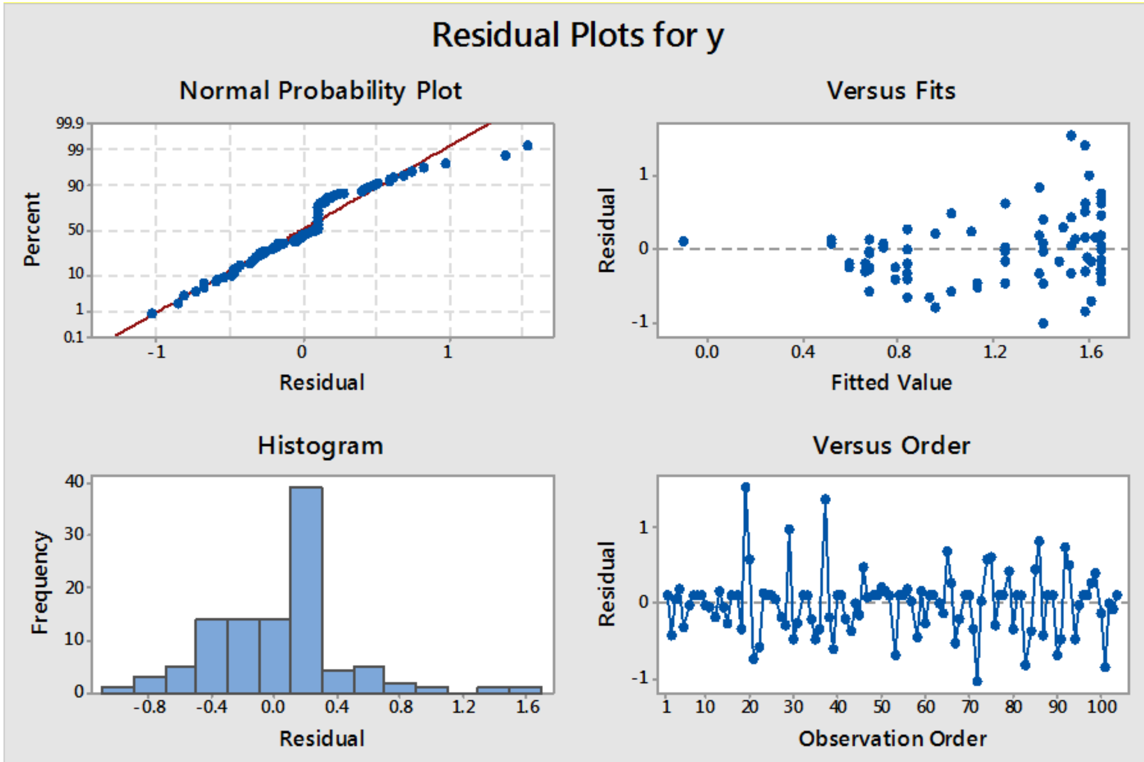

Figure 4.4 - Minitab© Residual Plots for Above-grade Manpower Loading Curves

Figure 4.4 above shows the residual plots generated for the manpower analysis. The first plot in the upper left hand corner of Figure 4.4 is the "Normal Probability Plot" to test the assumption of normality. A linear relationship within this plot is desired, so this first plot tends to check out as the "Residual" vs. "Percent" falls in a fairly straight line with slight curve in the middle. The bottom left plot in Figure 4.4 above is the "Histogram" plot. For this plot, the desired outcome is a bell shaped curve with the majority of residuals falling around 0, indicating a normal probability distribution. From the "Histogram" plot above, the frequency of the residuals tend to fall in a bell shape, with the results skewed to the left of 0.00. The final plots to check are the "Versus Fit" plot and the "Versus Order" plot, both of which are shown in the right hand side of Figure 4.4 respectively. For both of these, the desired outcome is for them to have randomness. The overall plot of residual vs.

fits is used to check the assumption of constant variance. From the analysis, the fitted plot does tend to be random, but also does sort of have an increasing in residuals to the right. This could suggest that further analysis and statistical plots be conducted to improve the model and check the assumption of constant variance. The residual vs. order is used to check the assumption of independent samples. This plot changes signs rapidly (but not one right after the other), but also does have random fluctuation pattern around the centerline which help indicate randomness. Further statistical analysis, transformations, and data collection should be done with future research to help confirm the initial model findings provided above with the regression analysis and to verify the assumptions made initially.

4.4 Manpower Loading Curves by Above-grade Activity

Along with the manpower loading curve for the entire substation project, the research also looked into manpower loading curves for individual above-grade activities. The resulted individual manpower curves, shown in Figure 4.5, highlight three main findings: activity manpower features, project milestones, and activity progression principles.

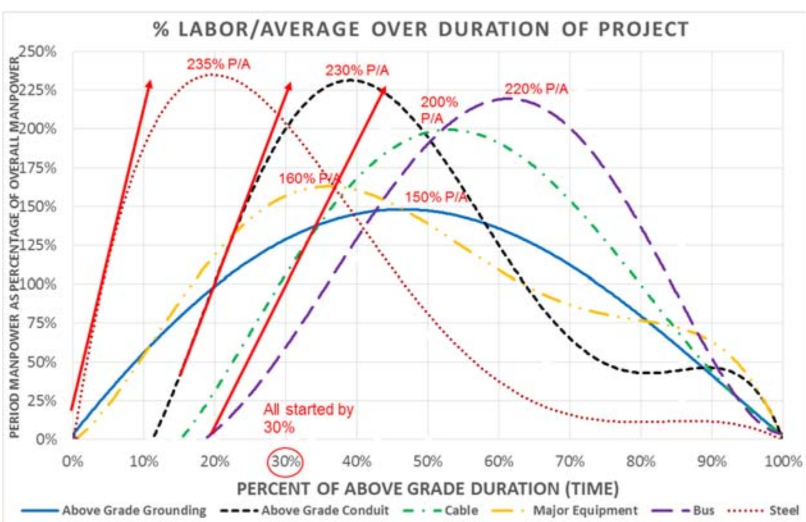

Figure 4.5 - Individual Manpower Loading Curves by Above-grade Activity

Activity Manpower Features

The building up of individual activities along with their P/A ratios are illustrated in Figure 4.5. Data analysis shows that steel, conduit, and cable installations have fairly steep manpower build-ups. Accordingly, practitioners should anticipate a high build-up rate for steel installation during the first 15% of project duration. Likewise, a high build-up rate for the conduit installation should be foreseen roughly in the time period between 15% and 30% of project duration. Similarly, a high build-up rate for cable installation should typically be expected in the time period between 20% and 40%. Moreover, Figure 4.5 reveals that steel installation usually has the highest P/A ratio (235%) at 20% of project duration, followed by conduit installation (230%) at 40% of project duration. On the other hand, grounding typically has the lowest P/A ratio (150%) achieved at 50% of project duration. This aligns with the fact that grounding completion does not typically impact the start of other activities.

Project Milestones

Based on data analysis, this paper deduces that all major project activities should start in the first 30% of project duration. This benchmark indicator should be used by practitioners as an early warning sign of poor project performance in order to mitigate negative impacts. Moreover, data analysis shows that steel installation, major equipment installation, and grounding typically start in the time period between 0% and 5% of the project duration. The time period between 10% and 25% of project duration typically experiences the start of the remaining three activities: conduit installation, cable installation, and bus work.

Activity Progression Principles

From a scheduling perspective, this paper provides sequencing principles for above-grade substation construction activities. Figure 4.6 shows a simplified linear sequencing pattern for the start of activities. Normally, steel and major equipment installations should start early in the project timeframe since remaining activities are dependent on them. Similarly, conduit installation needs to start prior to cable installation. However, these findings do not dictate a finish-to-start relationship between activities. Instead, reasonable overlapping normally takes place as shown in Figure 4.5.

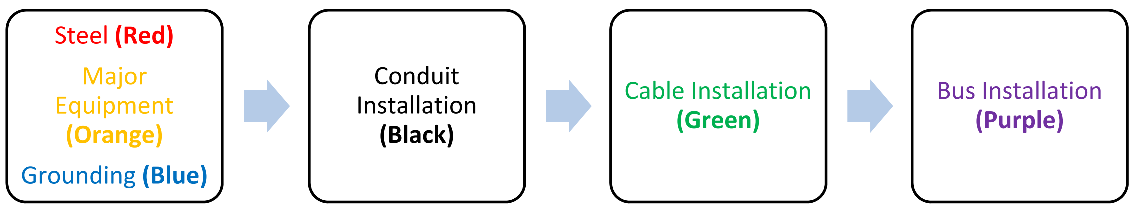

Figure 4.6 - Simplified Linear Sequence of the Start of Above-grade Activities

4.5 Overall Project S-Curve

Along with the manpower loading curves, typical S-curves are another means for illustrating how labor hours can be planned or expended over time and to develop benchmark indicators. For the substation research, this was done by plotting cumulative labor hours for the 14 projects over time in Microsoft Excel, and then running a regression analysis for the plotted points. Figure 4.7 below shows the analysis that was conducted, with the regression trend line plotted as a solid blue line. From this, it can be seen that the trend line fits well with the data points with a high R^2 value of 0.972.

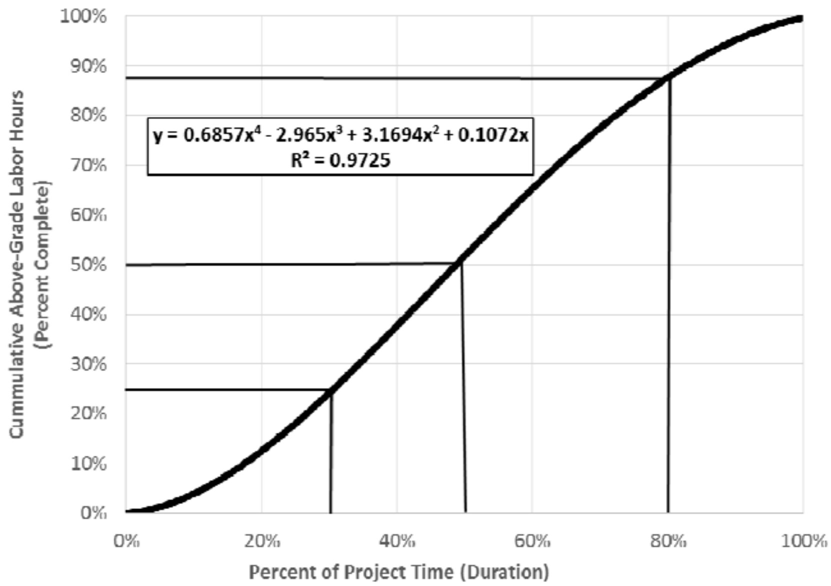

Figure 4.7 - S-Curve for Overall Above-grade Activities

The S-curve trend in Figure 4.7 also provides several project milestone control points for planning and tracking of projects. These project milestones are shown with black lines at different project time durations. For example, at around 30% project time duration, the project should have only expended or planned to expend approximately 25% of the total labor hours. Along with this, it can be seen that at around 50% of the project duration, approximately 50% of the project labor hours should be expected to be completed. Finally, at 80% project duration, the project should be approximately 85-90% complete in terms of labor hours. These benchmark checkpoints and overall S-curve trends shown above are consistent with previous research conducted within the mechanical and electrical building industry. For example, for mechanical projects, at a project duration of 30% the percent labor hours completed was approximately 20%. (Hanna 2010) Overall, this can be a useful tool with benchmark indicators to reference when planning and tracking hours expended on the project.

Along with the milestone checkpoints, the S-curve can also be plotted with typical upper and lower bounds across the duration of the project. The control points for this research were done in Excel by using a similar process previously established in the WDOT research. (CMCS 2012) This involved taking blocks of time ranges, calculating the average percent of time, and the average percent of hours for those specific time ranges. The block of time ranges were then plotted along the X-axis. The control points were then calculated by adding and subtracting the standard deviation to the average labor hours. The control points were then plotted along the Y-axis and combined within the chart shown earlier in Figure 4.7.

The data for this procedure can be seen below in Table 4.1 with the plot of the data then shown below that in Figure 4.8. From these control points, a range approach can be used to further identify deviations in the labor hours. For example, if a project is being monitored at time duration of 30% (X-axis) and is determined to have expended 40% of the labor hours, this should be a red-flag to the project team to review as it is already outside the typical upper bound for labor hours. This allows for earlier detection of deviations and potential mitigation of future labor overruns. These ranges can also be adjusted for different deviations depending on the risk of the project.

Table 4.1 - Control Points Calculated for the 14 Sample Substation Projects.

Percentage of Project Duration	Number of data points	Average Percentage of time	Average Percentage of labor hours	Standard Deviation of labor hours	(+) Standard Deviation	(-) Standard Deviation
0%		0%	0%	0%	0%	0%
0%-19.9%	13	16%	8%	5%	13%	4%
20%-39.9%	15	31%	25%	8%	32%	17%
40%-59.9%	17	50%	53%	13%	66%	40%
60%-79.9%	15	70%	78%	11%	88%	67%
80%-99.9%	19	86%	92%	6%	97%	86%
100%		100%	100%	100%	100%	100%

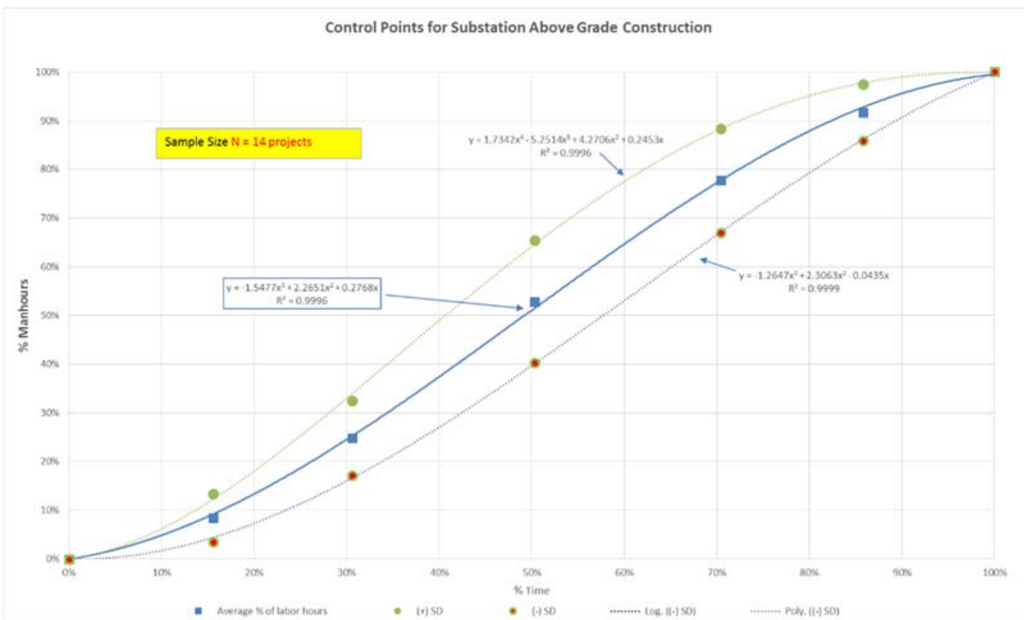

Figure 4.8 - S-Curve for Overall Above-grade Activities with Control Points

In addition to the Excel analysis shown above, the data points were plotted within Minitab© to confirm the S-curve research findings and regression analysis. From the results of the third order regression analysis, the R^2 value for the cumulative S-curve was calculated within Minitab© to be around .97. Again, this is a high R^2 value which indicates that the S-curve model generated from the 14 projects fits very well with the data set. This model S-curve is shown below in Figure 4.9 with a solid line, while the dotted lines represent prediction intervals (PIs). The PI lines are similar to the control points shown earlier in Figure 4.8 in that they provide a range of values for outputs (+/-) 5% (95% confidence interval) from the typical value of interest for project teams to compare against.

The results from Minitab© also include the calculated S-value which indicates the standard error of the estimate. For model fits, a smaller S-value is desired as it further indicates that the data points fit close to the fitted line. (Frost 2014) As seen below in the right hand side of Figure 4.9, the S-value for the cumulative substation S-curve was calculated as S=0.0638. This, along with the high R^2, initially suggests that the model generated fits well with the data points observed.

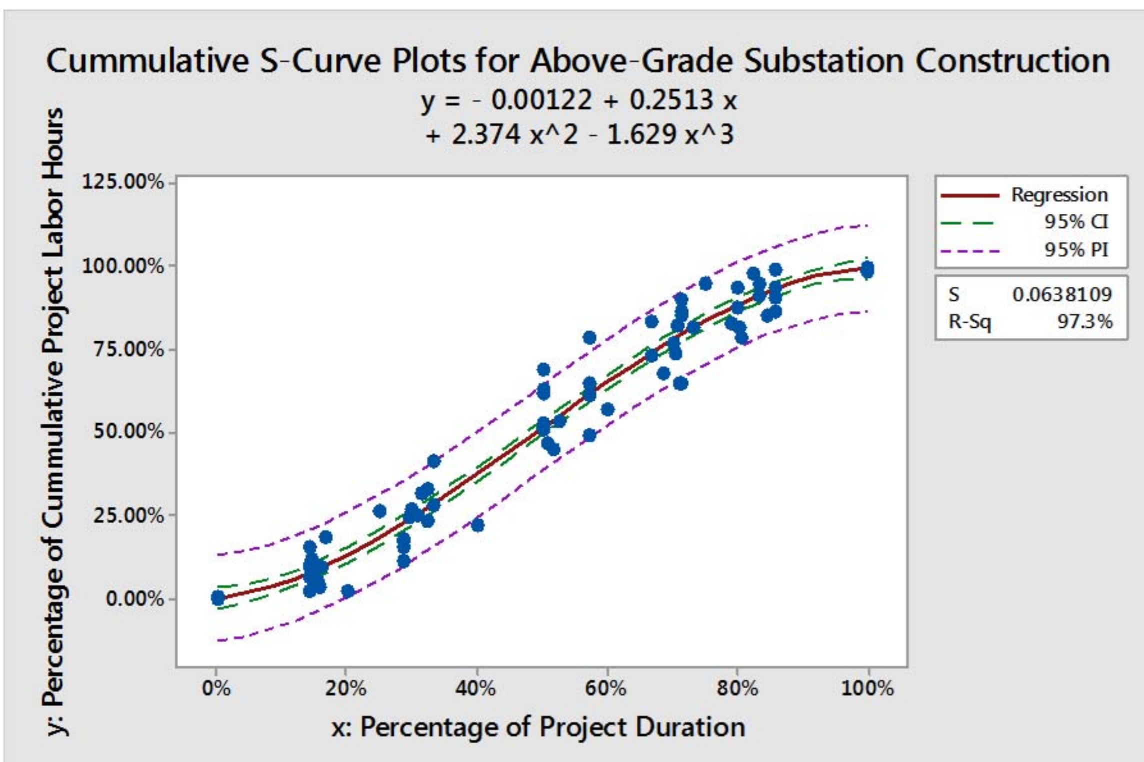

Figure 4.9 - S-curve Minitab© Regression Analysis for Overall Above-grade Activities

Along with the S-curve Minitab© plot, Minitab© reports were also ran to calculate the statistical P and F-values which can be further used to check the results generated from the data set. From Minitab©, the P-value and F-Values for the cumulative S-curve cubic model were calculated as 0.000 and 43.14 respectively. For this research, our null hypothesis (H_o) (devil's advocate) would be that the model fitted has no correlation (no predictive capability) with the data collected. Our alternative hypothesis (H_a) would then be that there is a correlation within the data collected. If the P-value is low, we reject our null hypothesis and state that our model fit does provide a correlation to the data set. With the P-value from the analysis at 0.000, we initially conclude that our model fits well with the data set, reject our null hypotheses and accept our alternative hypothesis.

Similarly, a large F-value indicates that we would reject our null hypothesis. With an F-value from the analysis of 43.14, we reject our null hypothesis again and conclude that the model again has initial predictive capability. So with both the P and F values checking out, we conclude that our model once again tends to fit well with the data set for the substation cumulative S curves. Please see Appendix F2 for additional Minitab© report summary with the P and F-values.

4.6 Minitab© Residual Analysis for Substation Above-grade Scope S-curves

Similar to the residual plots discussed in Section 5.2.2, this was also done for the S-curve results above to initially check the model for adequacy and to check the assumptions made earlier. Figure 4.10 below shows the residual plots generated for the S-curve analysis. The first plot in the upper left hand corner of Figure 4.10 is the "Normal Probability Plot". A linear relationship within this plot is desired, so this first plot appears to check out as the "Residual" vs. "Percent" tends to fall in a fairly straight line. The bottom left plot in Figure 4.10 above is the "Histogram" plot. For this plot, the desired outcome is a bell shaped curve with the majority of residuals falling around 0, indicating a normal probability distribution. From the "Histogram" plot, the frequency of the residuals primarily fall along 0.00 with a bell shaped pattern, so this tends to check out as well. The final plots to check are the "Versus Fit" plot and the "Versus Order" plot, both of which are shown in the right hand side of Figure 4.10 respectively. For both of these, the desired outcome is for them to have randomness. The overall plot of residual vs. order appears to be random around the centerline and doesn't seem to have any glaring patterns. The fitted value vs. residual also appears to be constant with a somewhat of a horizontal pattern, and minimal fanning. This helps support and initially indicates the assumption of constant variances to be true. Additional data collection, statistical analysis, and model checks should be done to further test the initial model results presented above and assumptions provided in this research.

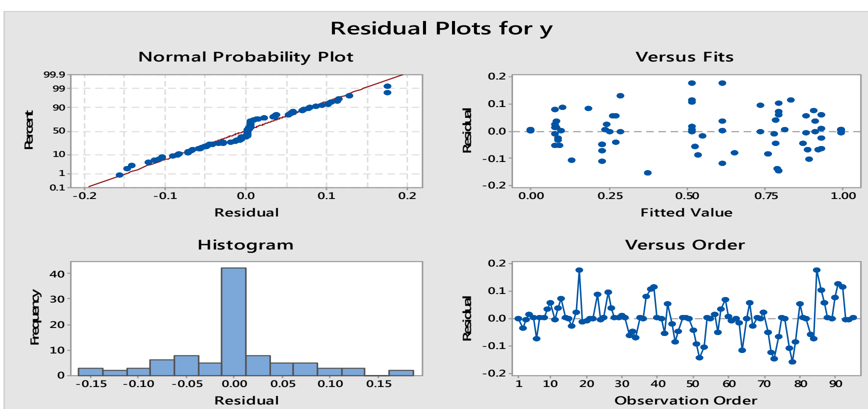

Figure 4.10 - Minitab© Residual Plot for Overall Above-grade S-Curve

4.7 S-curves by Above-Grade Activity

Similar to the WBS manpower loading curves discussed in Section 4.4, S-curves were also developed for individual substation above-grade activities. This provides typical trends for construction sequence and input as to how the activities ramp up over time. These high level trends for the substation research can be seen in Figure 4.12. From this, the sequence discussed earlier can also be confirmed and is summarized again with the flowchart below in Figure 4.11. The R^2 values for each above-grade task are again high (~.8-.9), indicating a strong model fit.

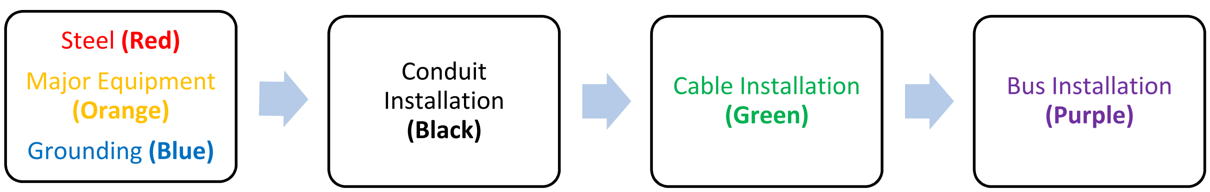

Figure 4.11 - Sequence Control Points for Above-grade Activities

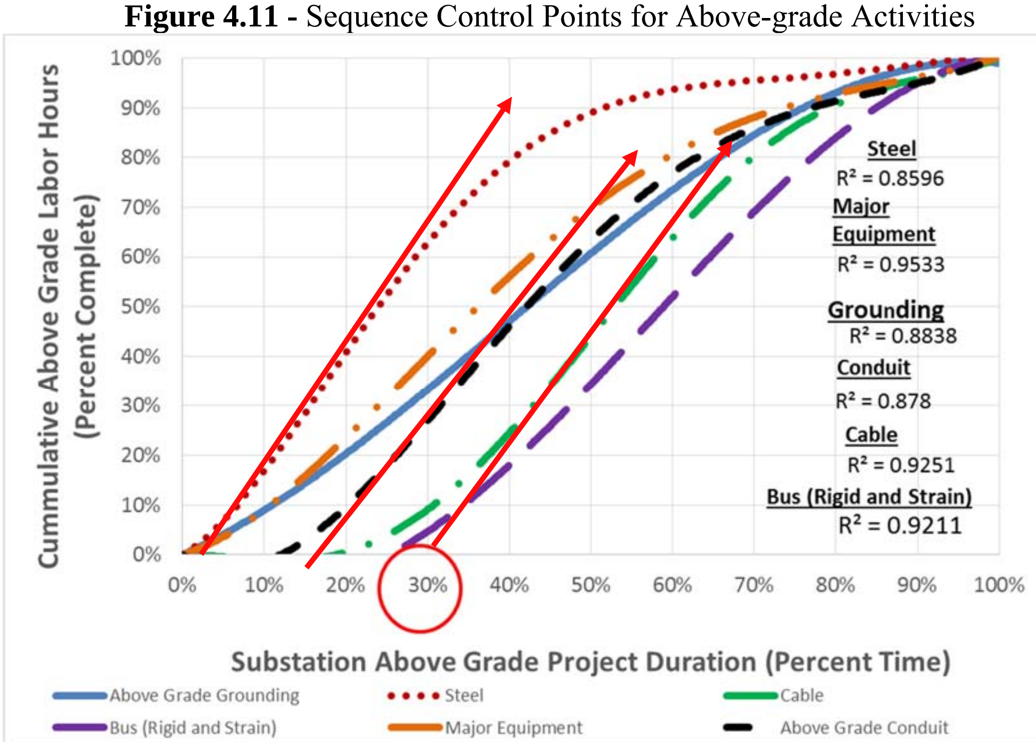

Figure 4.12 - S-curve for Above-grade Construction of Substations

From Figure 4.12 above, it can again be seen that steel, conduit, and cable installations typically have a fairly steep ramp of cumulative manpower with both of these having a fairly steep-linear line. Also, the figure above again demonstrates that at 30% project duration, all above-grade activities should typically be started and/or in progress. Once the project is around 50% time duration, steel and conduit should primarily be done, and the cable and bus installations should be about 45% and 35% completed respectively. These project duration points can again be used as a high-level milestone check for planning and tracking of a project. For example, during the planning of a project if all activities are shown to start around 15% time duration, the project team could question if the schedule is too aggressive and discuss why that might be. It also can be used for tracking of a project to check for production issues as labor hours are actualized. For example, if a typical substation project is ongoing and reporting at 50% time duration that the steel is only at 30% labor hours complete, this should initiate a warning sign to the project team for them to stop and review the projects production performance as it might be critically falling behind a typical schedule.

4.8 Activity Contribution Factors (ACFs)

The results above provide a good means for checking how the labor is planned and tracked over the duration of the project with typical control point indicators. One other method to check the overall project during the planning stage for estimate accuracy is to determine the activity contribution factor (ACF). For this paper, ACF is defined as the typical labor hour percentages per construction activity. The ACF can be used not only for determining high level estimates, but to also run a quick check of an estimate.

For this research, this was initially done within Excel by taking a ratio of the above-grade activity labor hours divided by the total above-grade labor hours of the project. The calculated percentages for each project were then averaged together and plotted in the pie chart below in Figure 4.13. From this, it can be seen that the installation of major equipment (~23%), bus installation (~25%), and cable installations make (~24%) up ~75% of the project labor hours. With only 25% of the other areas compiling the rest of the labor hours, a typical 80-20 percent rule should generally be used for planning and monitoring of tasks.

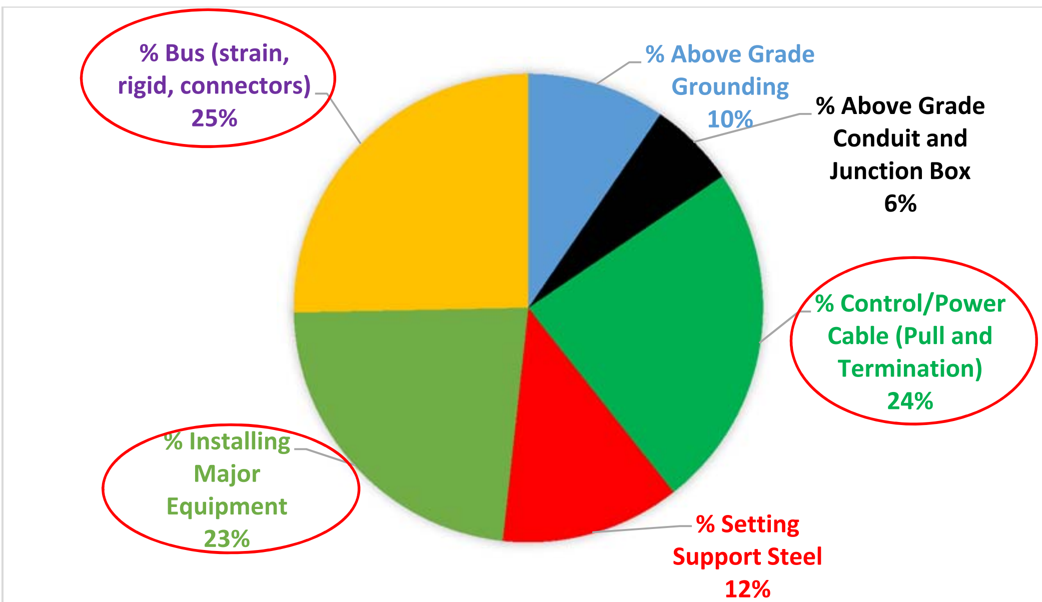

Figure 4.13 - Typical Percentage of Labor Hours per Above-grade Activities

Along with the pie chart above, which contains information based on all types of substation projects, a table was set up to see if the type of project has significant impact on the averages per task. Table 4.2 below summarized these findings. From the results presented below, the type of project doesn't seem to significantly impact the averages lists as the major above-grade activities, such as cable installations, major equipment, and bus installation still comprise the majority percentage of the labor hours. From this, it can be seen that for the majority of the projects, around 75% of the labor hours should fall within these activities. These items are boxed in red below in Table 4.2.

Table 4.2 – Percentage of Labor Hours per Above-grade Activities

Calculation	% Above Grade Grounding	% Above Grade Conduit and Junction Box	% Control/Power Cable (Pull and	% Setting Support Steel	% Installing Major Equipment	% Bus (strain, rigid, connectors)
Average New (Greenfield) N = 8	10%	7%	23%	11%	23%	26%
Average Addition or Expansion N = 6	8%	5%	24%	15%	23%	25%
Average Change in Voltage N = 9	8%	6%	24%	12%	24%	26%
Average Substation Switching N = 5	12%	5%	24%	13%	21%	24%

One additional statistical analysis that can be done for ACFs is to develop a box-and-whisker plot analysis, also known as a boxplot. A box-and-whisker plot is used as a visual plot to understand the distribution of the averages and to show the median. This plot also shows variability of the averages, typical tendencies of the data set, outliers, and upper and lower quartiles. (Minitab 2014) This can be beneficial to project teams as it provides more of a range of values approach for them to review against instead of a straight, single point average. For this substation research, the data calculated within Excel was taken and copied into the Minitab© statistical software package. Using Minitab's© boxplot generating tool, the following results shown in Figure 4.14 were generated.

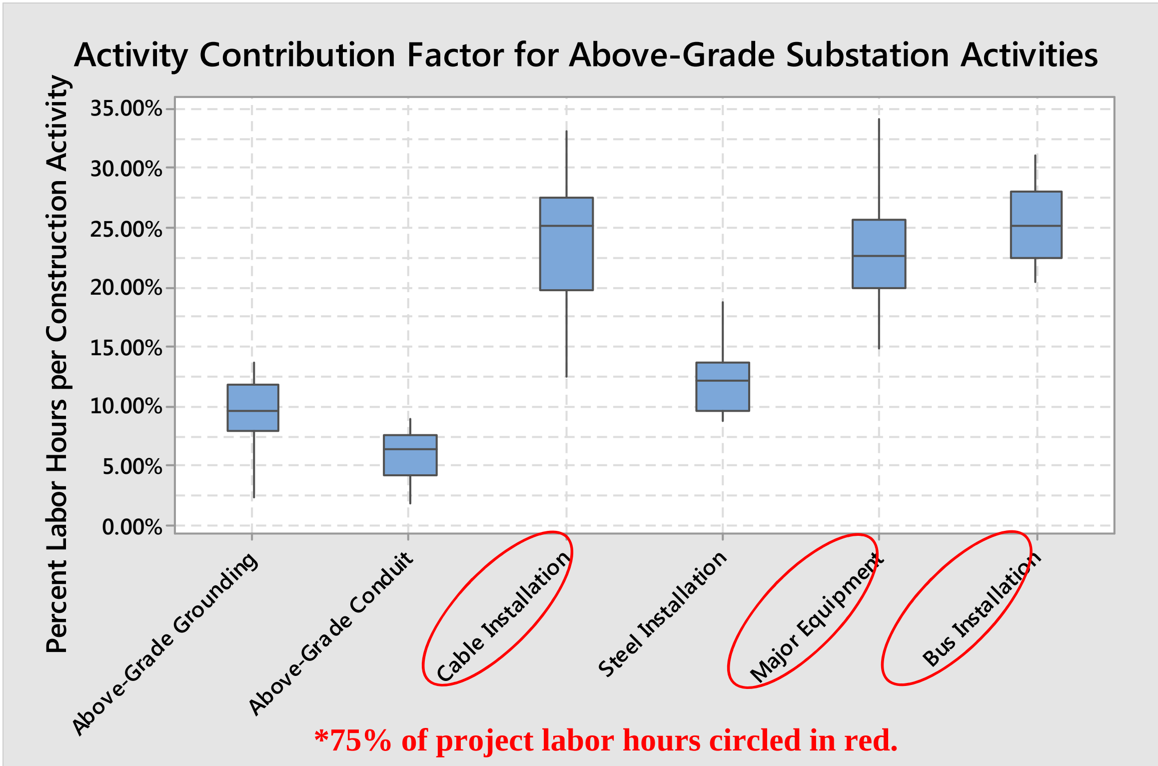

Figure 4.14 - Activity Contribution Factors (ACFs) of the Above-grade Activities

From the Minitab© boxplot above, the results infer that bus (~25%), cable (~25%), and major equipment (~23%) installations have the highest ACFs, collectively comprising approximately 75% of above-grade project labor hours. Therefore, it is recommended that practitioners should utilize more time for planning and tracking these activities. Moreover, the upper and lower quartiles of the box-and-whisker plots show that these activities have high variability with regard to their ACF. This variability can be attributed to the fact that these activities are typically impacted by different substation types, voltage classes, and design configurations.

On the other hand, grounding (~10%), as well as conduit (~6%), and steel installations (~12%) have the lowest ACFs, collectively encompassing around 25% of above-grade project labor hours. Also, the upper and lower quartiles demonstrate that these activities have the lowest ACF variability. This can be explained by their minimal design impact on the functionality of the substation.

4.9 Typical Substation Schedule Durations (Box-and-Whisker Plots)

One additional data point that project teams can utilize for planning of a project is to research typical schedule durations. The schedule durations can be used to determine how long a substation project and specific activities will typically take. For the substation research presented here, the schedule duration is defined from above-grade start activity (typically Steel setting) up thru substantial completion of above-grade activities (typically completion of bus installation). Dates from the schedules were pulled for these activities, inputted into excel, and time durations were then calculated. From the results, a typical substation project duration ranges from 10 weeks to 40 weeks, with an average duration of ~23 weeks.

Similar to the boxplot analysis above for typical labor hour percentages, a box-and-whisker plot was generated for the schedule durations as well. The results for this research analysis can be seen below in Figure 4.15. For this analysis, three items were plotted within the boxplot. This included average duration for all projects, average duration for primary voltage of 139-69kV, and average duration for primary voltage of 345kV only. This breakout provides visibility on how the voltage classes may impact the labor hours for a project. It also allows the project team to see upper and lower boundaries of schedule durations.

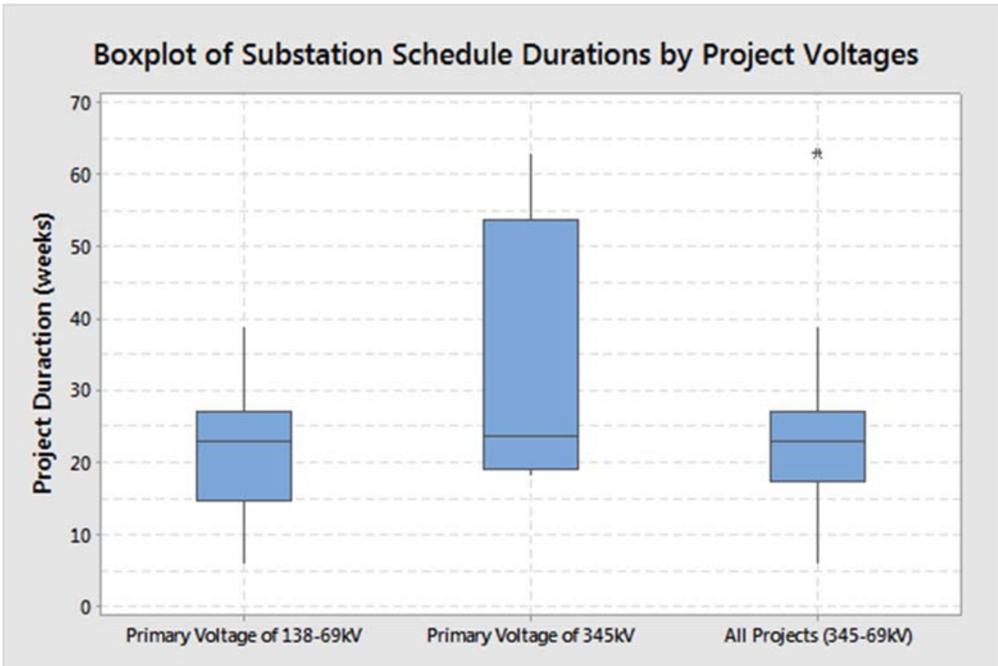

Figure 4.15 – Box-and-whisker of Substation Schedule Durations by Primary Voltage

From the boxplot above, it can be seen from the research data that all substation projects typically take ~18-25weeks. The plot above also shows that the 345kV projects gathered typically longer than the primary voltage of 138-69kV projects. This makes sense as the equipment for 345 kV projects becomes larger, clearances between buswork becomes greater, and larger conduits and cables are generally needed. These factors all result in extra manpower needed to complete the tasks. Yet, as shown earlier, the individual WBS tasks still maintain similar average percentages of labor hours between the different project types.

Also, the boxplots above provide upper and lower quartiles for the different project voltages to check against. For example, for the 138-69kV primary voltage projects, it could be more common to see projects with a range of 15-25 weeks. If a project is initially scheduled for primary voltages of 138-69kV to only take 10 weeks, this schedule might be too compressed and needing longer workdays to complete within the time period. A compressed schedule, which can involve working 6-10 hour days or 7-10 hour days, typically results in loss of production and inefficiencies. (Whiteside 2006) The project team should question this schedule as it tends to be aggressive when compared against these typical results, and determine if it changes are needed and adjust accordingly.

4.10 Summary

Chapter 4 discussed the major findings of the substation above-grade scope research. The regression analysis ran within the labor hour data over time produced manpower loading curves and S-curves that allowed typical benchmark indicators and control points to be identified. Results for typical percentages of labor hours per above-grade activity and schedule durations were also developed with boxplots used to further display the results. Chapter 5 will highlight best practices that were identified to be used for the projects research.

CHAPTER FIVE: BEST PRACTICES

5.1 Introduction

Along with developing standard manpower loading curves and S-curves, the research identified other typical Best Practices to complete objective 2 of the research. Best Practices include tools that the project teams utilized to help aid in establishing project success, such as reporting and tracking mechanisms, and establishing a Work Breakdown Structure (WBS). The following sections will discuss additional Best Practices that were identified and how they could potentially be used to improve substation project outcomes.

5.2 Work Breakdown Structure (WBS) and Substation WBS Example

Work Breakdown Structure (WBS) can be used to break down a project into manageable work components. This allows for better overall scope management and provides a visual structure of the work to be completed. Once a WBS is set up and understood by the team members, it can then be used to establish accountability, plan the project, and provide a framework for managing cost and schedule control.

For the substation projects researched, establishing a WBS was identified as a useful tool for either the electrical owner or contractor to put together. Based on the research and data collected, a sample WBS structure was put together for the above-grade scope for a typical new substation project. Figure 5.1 below provides a typical substation WBS example. The example provided bellow lists the above-grade activities that need to be completed. With substation WBS tasks of cable pulling, bus installation, and major equipment making up

75% of project hours as shown in Chapter 4, the research team recommends that these tasks be broken out in more detail in the WBS. For example, bus installations could have lower tasks to plan and track to, such as breaking out rigid and strain conductor bus as separate work packages. Each of these work packages could then also have individual tasks underneath them to break out further as shown below.

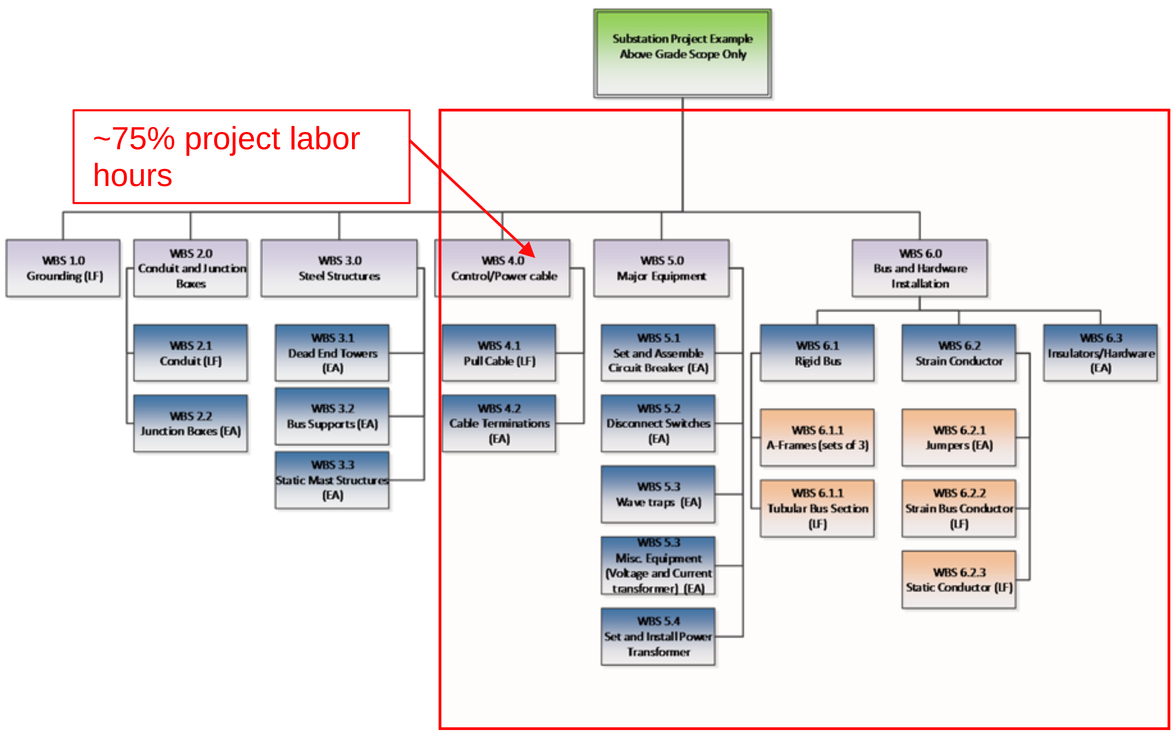

Figure 5.1 - WBS Example for Typical New Substation Above-grade Activities

Even with these recommendations, a contractor and or owner should review the WBS early on in the project and determine what level of detail is needed for the specific project. This will help ensure that all the tasks needed to complete the substation scope of work is captured and clearly defined. For example, other tasks such as steel structures could be broken out further depending on the specific difficulties, type (Voltage, size functionality), and duration of each project.

5.3 Field Tracking and Timesheet Reporting

Once the WBS is set up early on in a project, the contractor should begin to determine how to then plan the project, track, and report out on the construction progress. The WBS can be used as an input to determine the level of detail to track to, and what specific items should be tracked and monitored closer.

From the research, several best practices in terms of tracking and monitoring were identified to help improve substation project performance. From the contractors researched, the best practices included establishing a resource and manpower plan to establish a baseline to track against for combined labor hours, establish a field report tool with timesheets by cost code to gather actual progress, and report status out to project team members and owner.

The contractors for the projects in this research typically established progress tracking tools that were populated in the field. Progress tracking of the project is important as it allows inputs into reports that management can use to evaluate progress, such as thru S-curves as discussed earlier. There are two components to the field tracking. This includes gathering the labor hours charged by the crews and the production units completed in the field for a certain time period.

The first step involves gathering labor hour information from the field in forms of time sheets. From the research, the two contractors had timesheets that documented the labor hours for each crew member, along with information on the work completed. This was done by coding the labor hours by a certain cost code that the contractor established within the WBS activity. For example, for conduit installation shown above as WBS level 2.1, the contractors might have assigned a cost code (or even multiple cost codes) of 2100 to have within their accounting system.

Along with the labor hours on the timesheets and associating them with a cost code or WBS task, small write-ups were also included at times on the timesheets to summarize the work that the crew did for the day. This can be valuable for later confirming that hours that were charged to certain cost codes on the time sheets are accurate when compared to the work that was actually taking place. Along with this, the general foreman or crew foreman should be reviewing the descriptions of work completed to make sure that they accurately describe the work completed for the associated time period. Figure 5.2 below illustrates a timesheet example that could be used as a reference for filling out the hours and associated task. A more complete timesheet example has also been provided in Appendix G1.

Daily Report - SS Timesheet Tracking Example

Date: Sample | **WO#: Sample**

Crew Foreman: Research Team Sample | **Project Desciption: SS Research Sample**

Employee Information			Production Codes & Hrs Worked - List Cost Code with Hrs (see codes below)															
			EX: 1000		EX: 2100													
Name of Employee	Employee #	Class	ST	OT	ST	OT	ST	OT	ST	OT	ST	OT	ST	OT	ST	OT	ST	OT
Sample Person	1111	Apprentice		2	8													

Production Units Completed for Date XX

Description, WBS activity, and Accounting Code			Unit of Measure	Units Completed	Description of Work Completed (Location, Qty, etc)
Description	WBS #	Cost Code			
Grounding	1.0	1000	LF	30	Installed 3-10' tails of grounding for steel cirbuit breakers at position 3
Conduit	2.1	2100	LF	50	Installed 50' of conduit. 30' at CB position 3 and 20' up steel support X

Figure 5.2 - Timesheet Example for Tracking of Labor Hours and Production Units

The second step in gathering field data is to determine how much work has been completed within a certain time period and to date. Tracking the units completed is important as it is used as a primary input in determining how productive the crews are. Productivity, or production was defined earlier in Chapter 1 as the ratio of units completed over the number of labor hours completed.

From the research, the contractors typically tracked production of work completed by actually measuring the physical units completed in the field. There were a few methods in which the contractor tracked these actual units completed. One method involved listing the number of units completed on the timesheets for each cost code. The crew foreman should take responsibility of reviewing and verifying these quantities before submitting the timesheets. This can be seen in the bottom right side of Figure 5.2 shown above. In this example, the quantity (LF) of grounding and conduit was filled out, along with a description of work completed for those tasks. This requires there to be clear description as to what work was completed as this can often cause some confusion for those later on that have to decipher and input the data on the timesheets, and what units within the site (actual location) were physically completed. Once the timesheets are submitted, these could be used by management staff to transfer the units completed over to a progress tracking.

Another alternative for tracking production that the research team identified is to establish a project productivity tracking sheet or chart. This can be done in several forms. One method is to set up a simple excel spreadsheet that identifies each WBS activity that has units to track. This sheet can be put up within the project trailer for crew members to see daily as a visual tool to see and track work completed. A sample of a productivity tracking sheet can be seen below in Figure 5.3.

SS Productivity Tracking Sheet (Units Completed and Planned Units Example Sheet)									
Description, WBS activity, and Accounting Code						Week 1		Week 2	
Description	WBS #	Cost Code	Unit of Measure	Total Baseline Units Planned	Total Actual Units to Date	Planned	Actual	Planned	Actual
Grounding	1.0	1000	LF						
Conduit	2.1	2100	LF						
Junction Box	2.2	2200	EA						
Dead End Tower	3.1	3100	EA						
Bus Support	3.2	3200	EA						
Static Mast	3.3	3300	LF						
Pull Cable	4.1	4100	LF						
Cable Terminations	4.2	4200	EA						
Circuit Breaker	5.1	5100	EA						
Disconnect Switches	5.2	5200	EA						
Transformer	5.3	5300	EA						
Misc. Equipment	5.4	5400	EA						
A-Frames (set of 3)	6.1.1	6110	Set						
Tubular Bus (rigid)	6.1.2	6120	EA						
Jumpers (per phase)	6.2.1	6210	EA						
Strain Bus	6.2.2	6220	LF						
Static Conductor (shielding)	6.2.3	6230	LF						
Insulators (set of 3)	6.3	6300	Set						

Figure 5.3 - Productivity Tracking Sheet Example for Tracking of Units Completed

The sample sheet above contains the WBS activity to track (with example of cost codes listed), the units that were planned, and then columns for tracking actual units completed by week. Along with the actual units to be populated, the project management team could also include planned units to be completed per week. This provides the crews with a visual target for tracking and monitoring the planned schedule of activities. If major changes occur with the plan, the team could then identify this and update the baseline plan date as needed.

Instead of using an excel sheet, one other visual tool that the team could use to track units completed is to utilize a general arrangement drawing (or drawing per each major WBS activity) that shows the substation above-grade scope of work to be completed. For example, a conduit plan could be plotted out on large drawing paper and placed up on the wall of the trailer. The crews could go in each day (or week ending timeframe) and highlight and date the progress of conduit work as it is completed. The General Foreman or management staff could then gather the results from these drawings onsite each week to summarize the production progress as it occurs. This tool might be more intuitive for the crews in the field to use, and also does a good project of showing what work needs to still be completed. The office personal could also use this sheet to go out into the field and quickly do a visual inspection of the items the crew highlighted as completed for accuracy. This could take some of the guesswork or uncertainty of the field in trying to determine how to track a unit as complete, and leaves it up to the management staff determine the inputs based on what is shown as completed.

One additional best practice further identified from this research is to establish definition of the activity cost codes for the field to use when tracking production. From this, the research team recommends (especially for larger substation projects) that the project team establish a list of the cost codes and describes what unit is being used to track it. For example, for setting of steel, the cost code for installing a bus support could be 3200 as shown in the figures above. The management team should then define to the crew what constitutes a completed unit for the activity. For example, it could be defined that 3200 is defined by units of EA, where one completed unit of EA involves installation of 1 steel bus support, per single phase. This can help avoid confusion for the crew and more clearly establish expectations for tracking of production. Also, it is recommended that the General Foreman go over the tracking expectations established by the team at the beginning of the project. This is important to do early on in the project to establish buy-in from the crews.

The above section discussed the inputs (labor hours and production units) that are needed for reporting of project progress and how they can be gathered. The following Section 5.4 will further discuss how the data collected is then typically used, and provide best practice examples for progress reporting sheets and timeframe of progress reporting.

5.4 Substation Progress Reporting

The next step after gathering the project date from the field is to summarize the project data, condense it down, and report out the current status project performance to team members. The goal of the progress reporting is to determine deviations or trends that can be drawn on a week to week basis or other reporting period. This would allow the team to find poor production trends, labor hour issues, etc. and take action as needed.

From the substation research, it was identified that progress reports were typically put together on a weekly basis by the contractor. These reports were put together by the contractors project controls (with assistance from the contractors accounting team), reviewed by the project manager, and then sent to the owner and other team members for review and analysis. Typical items that were considered to be included within the reporting tool as a best practice include the following: WBS activity code (or contractor code) and activity description, definition of units, budgeted production units, budgeted labor hours, actual production units, and actual labor hours.

Figure 5.4 below shows an example of a substation progress report that could be used for a team to summarize the results, with columns A-F and Column I containing the main items discussed above. As a further step, the research team would recommend that for larger substation projects that the project management team include information on production rates or earned hours within the sheet. By reporting out the actual unit rates to date (as defined in Column M below), along with the baseline production unit rates (as defined below in Column L), this allows the project team to see what activities might be performing lower than planned and react as needed.

[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]
SS Above Grade Scope WBS Information			Budgeted Information		Labor Hours		Production Units		Performance			
WBS Higher Level	WBS Task	Activity/Task	Budgeted Labor Hours	Budgeted Units	Actual Labor Hours (To Date)	Percent Labor Hours Complete (To Date)	Actual Units Completed (To Date)	Percent Units Complete (To Date)	Earned Labor Hours	Activity Performance Factor	Baseline Unit Rates (Labor Hours/Unit)	Actual Unit Rates (Labor Hours/Unit)
1.0 Grounding	1	Grounding	Estimate	Estimate [LF]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
2.0 Conduit	2.1	**Conduit**	**Estimate**	**Estimate [LF]**	**∑ (timesheet)**	**[F] / [D]**	**∑(Field Measured)**	**[H] / [E]**	**[L]x[H]**	**[J] / [F]**	**[D] / [E]**	**[F] / [H]**
	2.2	Junction Box	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
3.0 Steel	3.1	**Dead End Tower**	**Estimate**	**Estimate [EA]**	**∑ (timesheet)**	**[F] / [D]**	**∑(Field Measured)**	**[H] / [E]**	**[L]x[H]**	**[J] / [F]**	**[D] / [E]**	**[F] / [H]**
	3.2	Bus Support	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	3.3	**Static Mast**	**Estimate**	**Estimate [EA]**	**∑ (timesheet)**	**[F] / [D]**	**∑(Field Measured)**	**[H] / [E]**	**[L]x[H]**	**[J] / [F]**	**[D] / [E]**	**[F] / [H]**
4.0 Cable	4.1	Pull Cable	Estimate	Estimate [LF]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	4.2	**Cable Terminations**	**Estimate**	**Estimate [EA]**	**∑ (timesheet)**	**[F] / [D]**	**∑(Field Measured)**	**[H] / [E]**	**[L]x[H]**	**[J] / [F]**	**[D] / [E]**	**[F] / [H]**
5.0 Major Equipment	5.1	Circuit Breaker	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	5.2	**Disconnect Switches**	**Estimate**	**Estimate [EA]**	**∑ (timesheet)**	**[F] / [D]**	**∑(Field Measured)**	**[H] / [E]**	**[L]x[H]**	**[J] / [F]**	**[D] / [E]**	**[F] / [H]**
	5.3	Transformer	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	5.4	**Misc. Equipment (PT, (**	**Estimate**	**Estimate [EA]**	**∑ (timesheet)**	**[F] / [D]**	**∑(Field Measured)**	**[H] / [E]**	**[L]x[H]**	**[J] / [F]**	**[D] / [E]**	**[F] / [H]**
6.0 Bus and Hardware	6.1.1	**A-frames (Set of 3)**	**Estimate**	**Estimate [EA]**	**∑ (timesheet)**	**[F] / [D]**	**∑(Field Measured)**	**[H] / [E]**	**[L]x[H]**	**[J] / [F]**	**[D] / [E]**	**[F] / [H]**
	6.1.2	Tubular Bus Section (R	Estimate	Estimate [LF]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	6.2.1	**Jumpers**	**Estimate**	**Estimate [EA]**	**∑ (timesheet)**	**[F] / [D]**	**∑(Field Measured)**	**[H] / [E]**	**[L]x[H]**	**[J] / [F]**	**[D] / [E]**	**[F] / [H]**
	6.2.2	Strain Bus Conductor	Estimate	Estimate [LF]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	6.2.3	**Static Conductor (Shie**	**Estimate**	**Estimate [LF]**	**∑ (timesheet)**	**[F] / [D]**	**∑(Field Measured)**	**[H] / [E]**	**[L]x[H]**	**[J] / [F]**	**[D] / [E]**	**[F] / [H]**
	6.3	Insulators (Set of 3)	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
Total Above Grade SS Scope			**Estimate**	**Estimate [EA]**	**∑ (timesheet)**	**∑([F] / [D])**	**NA**	**∑ [J] / ∑ [E]**	**∑ [J]**	**∑ [J] / ∑ [F]**		

Figure 5.4 - Tracking Sheet Example for Typical New Substation

Earned hours can further be used to associate labor hours to the physical work completed by the project. This involves taking the budgeted unit rate that was estimate for activity

(Column L) and multiplying it by the actual units completed to date (Column H). Once the earned hours are calculated (Column J), the team can use the earned hours to determine the activity performance factor. The activity performance factor (Column K) is calculated by dividing the Earned Hours (Column J) by the Actual Hours (Column F). If the ratio value calculated in column K is greater than 1, the activity is producing better than planned. If the ratio in column K is less than 1, this is an indicator that the activity is producing worse than planned. The performance values can also be plotted over time to show the productivity trends for an activity. An example of a Performance Factor Profile is provided below in Figure 5.5 with the values greater than 1showing production better than planned. (Hanna 2010)

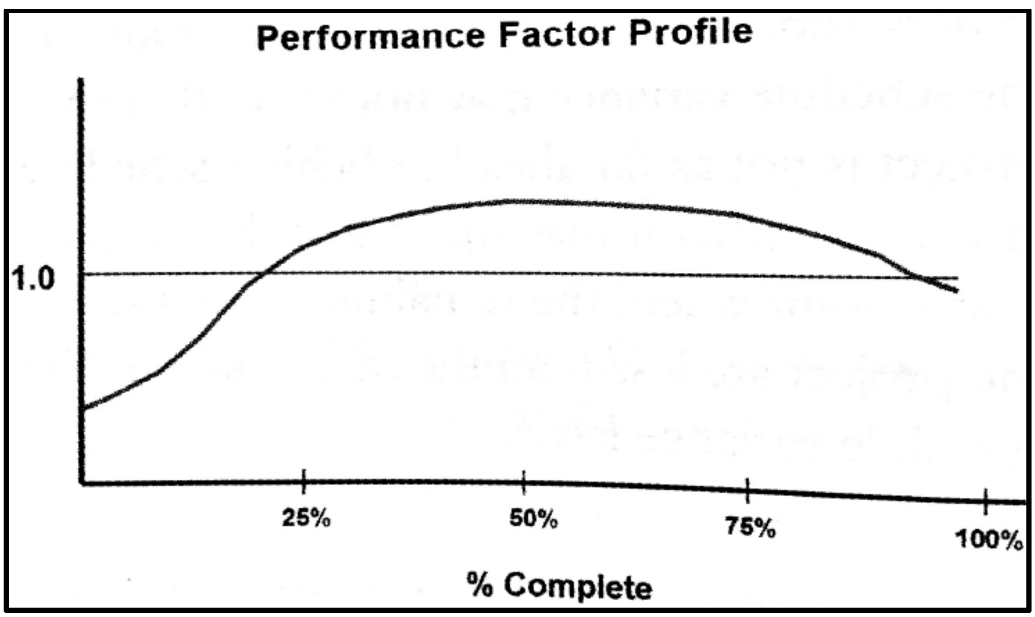

Figure 5.5 - Performance Factor Profile Example (Hanna 2010)

5.5 Summary

The section above highlighted a few other best practices that were identified within the substation research. Along with establishing S-curves and manpower loading curves to plan and monitor against, the project team should utilize a WBS throughout project planning and tracking. An example of a typical substation WBS was provided for a new substation project. The research team recommends that the project team utilize the WBS to establish a framework for timesheet and progress reporting. In addition, weekly progress reporting sheets containing actual labor hours, units complete, and other production rates should be utilized weekly by a project team to monitor project performance.

CHAPTER SIX: APPLICATIONS, RECOMMENDATIONS, & CONCLUSION

6.1 Summary

Labor control on construction projects is an important project management and team function to reduce project cost and improve crew production. Successful control of labor hours during estimating and tracking of a project actuals early on can have a significant impact on the overall success of a project.

Chapter 1 of the paper discussed the need to establish labor control indicators within the electrical substation sector via benchmarking tools. The first section of definitions defined substation project types and function, how they are integrated within the electrical transmission grid, and provided an overview of the above-grade equipment components. The second portion of the definitions provided the reader with key construction industry definitions that were applicable to understanding the research presented. These included definitions such as production, benchmarking, S-curves, and manpower loading curves. The problem statement, objectives, scope, and methodology were then all highlighted. The problem within the electrical industry is that there is a lack of labor hour benchmarks and control points when compared to other industries. This is becoming more critical to establish for substation projects as the electrical industry is projected to have approximately $880 billion of projects within the next two decades. As a result, the goal of this research was to utilize actual project labor hours and identify typical labor control points. The scope involved a comprehensive data collection for the above-grade activities of “well-executed” substation projects from upper Midwest owner completed by two different construction contractors. The methodology used for researching the projects involved developing a survey, gathering contractor input from survey information and contractor data input sheets, populating data into excel, analyzing the data for specific model trends, checking the analysis for adequacy, and reporting of research results. Assumptions were also documented within this section.

Chapter 2 discussed literature that was reviewed within the industry to help establish the need and typical use of benchmark indicators. Prior research results established within the HVAC and WI-DOT were presented to show what has been done in other industries to date, and how benchmark indicators can be utilized by project teams to improve project performance. For example, standard manpower loading curves and S-curves have already been established for mechanical contractors. These can then be used as control points for estimating and tracking of actual labor hours. The end of this chapter re-iterated the need for electrical industry labor benchmarks as there is a general lack of research for labor hours and control indicators in this sector.

Chapter 3 summarized the project data that was collected. A total of 14 projects from an upper Midwest owner completed by two different contractors had data gathered based on the survey results and input sheets provided. Specific project characteristics, such as voltage class, number of labor hours, and type of project were discussed. The major types of equipment characteristics, such as quantities of circuit breakers and transformer, were also presented to provide input as to the type of projects for future comparison.

Chapter 4 presented the analysis and the model trends developed for the researched electrical substation data that was discussed in Chapter 3. The analysis provided initial manpower loading curve and S-curve model trends with R^2 values of 0.760 and 0.970 respectively. This was done cumulatively for total above-grade labor, but also broken out for individual above-grade activities provide input on the sequence and build-up of work activities. Control points were also added to the typical S-curve generated to provide upper and lower typical boundaries. In addition to the model curves and control points, typical breakout of project labor hours by WBS activity and schedule durations were also established. Boxplots were utilized used for these benchmarks to provide a more visual average and range of values. The section also provided initial statistical checks for the model results by conducting regression analysis and residual analysis plots via excel and Minitab©, and identified recommendation for future statistical research and checking of the models.

Chapter 5 presented additional best practices that were identified to be used or recommended for electrical substation projects. Best practices discussed included the need for a project Work Breakdown Structure (WBS). A WBS example was also provided as a starting point for a typical new substation project. Methods for gathering actual labor data and production from the field via timesheets and tracking sheets, along with examples, were also discussed. The last item within this section went over the typical frequency of reporting, a progress reporting sheet example, and a few additional reporting items that could be beneficial to the project team.

6.2 Applications

The research findings presented within this paper can be beneficial for electrical substation practitioners. The research provides typical labor control points that project team members can utilize to check initial estimates for adequacy and to better control labor on projects. The results also provide typical, high level control indicators for planning and tracking of actual labor hours. When planning a project, a contractor can compare their labor plan to that of the typical S-curve and benchmark indicators and see if they might be too aggressive. This similar process can also be done during construction by plotting the actual labor against the typical benchmark indicators. This provides baseline control points for the project team to identify and react (as needed) to poor performance earlier.

The research also ultimately provides contractors with a mechanism and framework for establishing their own in-house benchmarks to compare against. It would be highly recommended for contractors to establish their own in-house benchmarks and control indicators for their specific niche of projects by using this similar research process provided. The examples of the WBS along with the timesheet and progress tracking tools can also be used as starting points if a contractor doesn't currently utilize these tools. These can be refined, modified, and improved upon within the organization as projects evolve.

6.3 Recommendations for Future Research

There are several recommendations for future research that could benefit the electrical substation industry. The first major recommendation would be to increase the substation above-grade scope project sample size of projects researched and increase the number of contractors included as the research here is limited to 14 projects from only two different contractors. By increasing the project sample size (greater than 30 projects) and adding more contractors to the database, further statistical analysis and review of the assumptions made can be done to check the validity of the models and typical results provided. In addition to adding to the project sample size, projects could be used and tested within the model as another method to check model validity. It would be recommended that two or more projects be used and ran within the model to validate this. Along with this, the additional data might help improve the manpower loading curves R^2 value and peak to average ratios.

Further statistical analysis could also be done to determine which characteristics of the project are statistically significant, or which activities have more statistical impacts on project outcomes. For example, it could be researched further to see if location, contract type, or bus design type have a significant impact on the labor production for these projects. In addition to this, the research could further be broken out to establish specific manpower loading curves for individual project types, such as S-curves solely for 138kV new substation projects based on the specific additional projects that are gathered.

Along with the recommendations above, future research could include the remaining scope of substation projects. This could include similar research for the below-grade scope of work activities such as site grading, foundations, stone installation, storm water management, below-grade conduit installation, etc.. Future research could also look into the breakout percentages for an entire substation project, such as percentage of above-grade scope to below-grade scope, and typical subcontractors involved. Along with this, typical equipment (tools) used for constructing substation projects could be researched along with their typical loading over the project. This could help determine how equipment affects crew production and project performance.

Further research could also be done with regards to the contract type of the substation projects. The research presented in this paper, as stated earlier in Chapter 1, was for time and material contract type. Additional research for other contracts, such as lump sum contract projects, could be done to see if the control points are in-line with each other. This could help project teams more specialize their control points for the specific type of project contract.

Finally, research into Earned Value Management and contractor reporting, similar to that conducted by Hanna previously in the HVAC industry, could be conducted. This could include a few case studies of substation project utilizing earned value management, establish tips for forecasting of labor hours, and identify typical performance factor profiles for substation activities and substation projects. By having a few case studies researched, it could be better understood whether or not substation construction labor follows the typical performance profiles identified in other industries, and how earned value can improve project forecasting.

6.4 Conclusion

Due to the large increases in planned capital funds for the electrical grid industry, it is vital to monitor and control the substation construction resources expended. This paper provides substation practitioners with initial typical control indicators to better plan and track their labor performance for above-grade activities, and provides the framework and recommendations for future additional research in this industry. These control indicators were developed through comprehensive data collection and analysis of 14 well-executed substation projects completed in the upper Midwest by two different contractors.

The research from these projects indicate initially that well-executed substation projects typically consume 30% of the total above-grade labor hours between 0 and 40% of the project duration. An additional 40% of the labor hours is consumed between 40 and 60% of the project duration. The final 40% of the project time consumes the remaining 30% of the above-grade project labor hours. The developed manpower loading curves further revealed that labor hours typically peak at around 50% project duration with an approximate peak to average ratio of 180%. Furthermore, data analysis shows that all above-grade project activities should commence by 30% of project duration. Finally, the results from the data analysis show that major equipment, bus, and cable installations have large activity contribution factors, comprising 75% of the substation above-grade labor hours. Best practices were also discussed to help substation contractors establish consistent labor reporting and tracking tools.

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APPENDIX B. GLOSSARY

Abbreviations:

CB = Circuit Breaker

kV = 1,000 Volts, kilo-volts

Labor Hours = Man-hours

SS = Substation or Substation Electrical Facility

WBS = Work Breakdown Structure

Definitions:

<u>Above-grade Conduit</u>

Above-grade conduit in a substation (known as "raceway") is typically installed to the major equipment, such as to the circuit breakers, and is used to protect the cable that is used to operate that equipment. (USDA 2001) There are various forms of conduit used for above-grade depending on the applications, ranging from different sizes of rigid PVC pipe, flexible conduit, and galvanized steel pipe. The type of conduit used today is commonly plastic PVC, mainly due to its ease of use, availability within the electrical industry, and low cost. (Heinemann et al. 2012) The above-grade conduit for major equipment typically runs from the ground trench, up to the cabinet or junction box that is used to terminate the cables. Conduit connections and terminations, such as 90 degree elbows and transitions from rigid to flexible connections, also are typical installations. Figure B1 below shows an example of a run of PVC conduit to a circuit breaker cabinet, circled in yellow below.

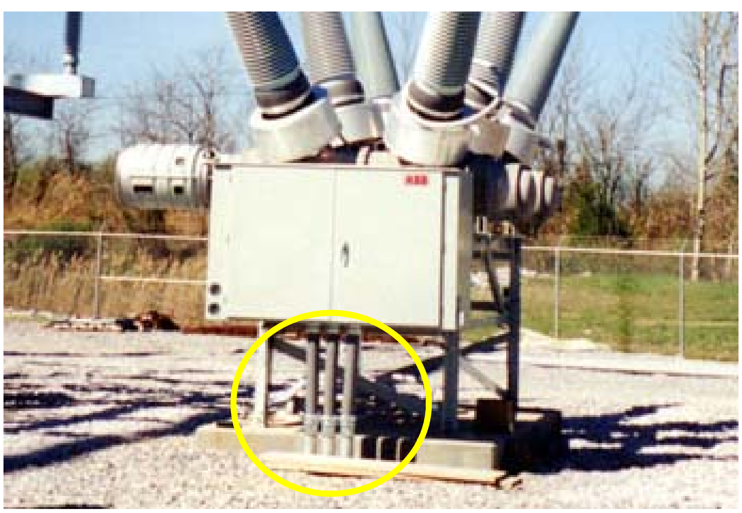


Figure B1 - Above-grade Conduit to Breaker Cabinet (Commonwealth 2015)

Above-grade Grounding

Above-grade grounding is also needed for the above-grade scope of work. This is done to ground steel structures, such as those for equipment stands or bus supports, ground major equipment such as circuit breakers, and ground perimeter fencing. (USDA 2001) Above-grade grounding, which typically consists of 4/0 copper, is tied to the steel structure and then connected to the installed ground grid that is part of the below grade substation work. (USDA 2001) Grounding is used within the substation to provide human safety by allowing individuals within the substation to not be exposed to an electric shock. Along with this, the grounding system is used to take electrical currents from faults to the ground where it is dissipated and also provides reduction in damages caused by lightning strikes. (USDA 2001) Figure B2 below shows an example of structure steel being grounded with copper (circled below in figure).

Figure B2 - Above-grade Grounding on Steel Structure (Watts Electric 2015)

Benchmarking

Benchmarking of past data includes gathering project cost metrics and labor to establish high level milestones and control points. The benchmark data can then be used as inputs or verification tools to check against estimates or actuals. (Bradshaw 2008) Benchmarking can also include research and development of standard manpower loading curves and S-curves for projects to identify project milestones (benchmark indicators) and or labor control points. (Hanna 2010)

Benchmark Indicators

Benchmarking indicators, or benchmark control points, are the key outputs from benchmarking that can be used to validate project estimates and actuals. This process involves utilizing past project data, such as labor hours, to establish typical project trends. The labor hour trends established can then be used by future project teams to serve as control points within the planning stage, and also used as monitoring of actual construction progress.

Buswork Installation (bus - rigid and strain, and jumpers)

Buswork (or bus) are the main structural components used in the substation for carrying the electrical current thru the substation facility. As discussed earlier, buswork can be arranged in different configurations to create several substation layout options. This includes ring bus configurations, breaker-and-a-half, single bus, etc. There are two main types of bus used within the different substations facility types, which include rigid and strain bus. Rigid bus (rigid conductors), as shown in Figure B3 below, are typically used in low profile type substations with lower steel structure supports. (USDA 2001) Rigid bus can be found within the site in different shapes and sizes, such as with the use of tubular aluminum as shown below in Figure B3. Selection of the size and type of bus used within the system depends on the current capacity needed for the design of the substation. (USDA 2001)

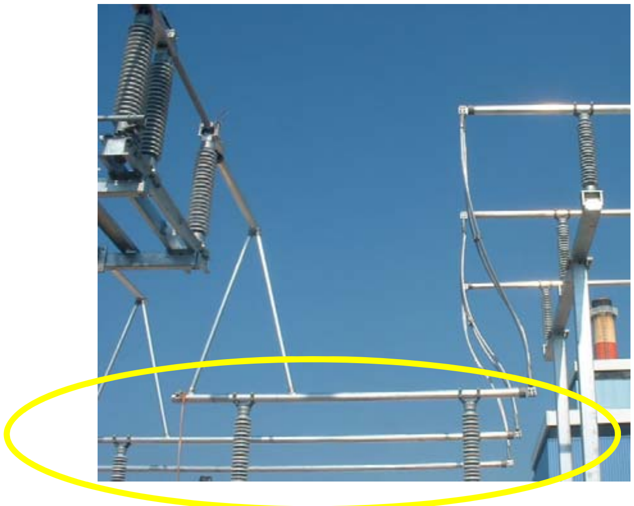


Figure B3 - Rigid Bus within a Low-profile Substation (JL Malone 2015)

Strain bus are also used for carrying current in the substation facility. The strain bus is typically composed of flexible conductors, such aluminum strand conductor. (USDA 2001) The size of the wire, along with the type of conductive material used all impact the overall ampacity of the substation. (USDA 2001) Strain conductors are typical within a lattice box structure to carry the electrical current within the structure. Figure B4 below shows an example of strain conductor used for carrying current within the box structure. Flexible conductors are also commonly used as "jumpers" within a substation. Similar to strain bus, jumpers consist of electrical conductor (such as aluminum strands of conductor) to serve as the electrical path connection from the rigid bus to the major piece of equipment. Figure B5 below shows jumper material used to connect from the main bus to a circuit breaker.

Figure B4 - Lattice Box Structure with Strain Bus (Fabrimet 2008)

Figure B5 - Jumpers to Circuit Breaker (University of Wisconsin-Madison)

Circuit Breakers (High-voltage Circuit Breakers, (CB))

A Circuit Breaker (CB), as defined in the RUS design for high-voltage applications, is a "device that closes and interrupts (opens) an electric circuit between separable contacts under both load and fault conditions." (USDA 2001) Figure B6 below shows a typical CB commonly seen inside a substation facility. This breaker type uses SF6 gas as the medium to interrupt the electrical current, whereas existing breakers typically used oil filled tanks. A CB is commonly seen for each phase, sits on a concrete foundation, and typically has disconnect switches on each side of the breaker for visual isolation. (USDA 2001)

Figure B6 - High-voltage Circuit Breaker; Gas Type (Utility Products 2014)

Control Cable (or cable)

Installation of control cable is another above-grade component of substation facilities. Within a substation yard, the above-grade scope of work involves pulling cable thru the conduit from the equipment cabinet and terminating it within the control house (equipment enclosure building). Control cable serves the function of sending metering and protection information for the major piece of equipment, and for providing backup DC power to the equipment. (Idaho Power Company 2011) Copper conductor is typically used within substations as the terminations can be made fairly easy with it.

Distribution Step-Down Substation

Distribution step-down substation facility is another type of substation found on the electrical grid system. These facilities are a key connection point within the electrical grid system to step down the high-voltage on the transmission line (69kV and greater) to the distribution voltage (12.5kV typical). They contain power transformers to step-down the voltage as noted above, and feeder exits on the distribution side. The distribution feeders provide multiple sources of power to the distribution facilities. (University of Wisconsin-Madison 2014) Figure B7 below illustrates this configuration in a plan view form, with the incoming/outgoing transmission voltage at 138kV being step-down via a power transformer to the distribution voltage. (University of Wisconsin-Madison 2014) This is the final transmission facility in the high-voltage grid system and the rest of power delivery is handled by the distribution system.

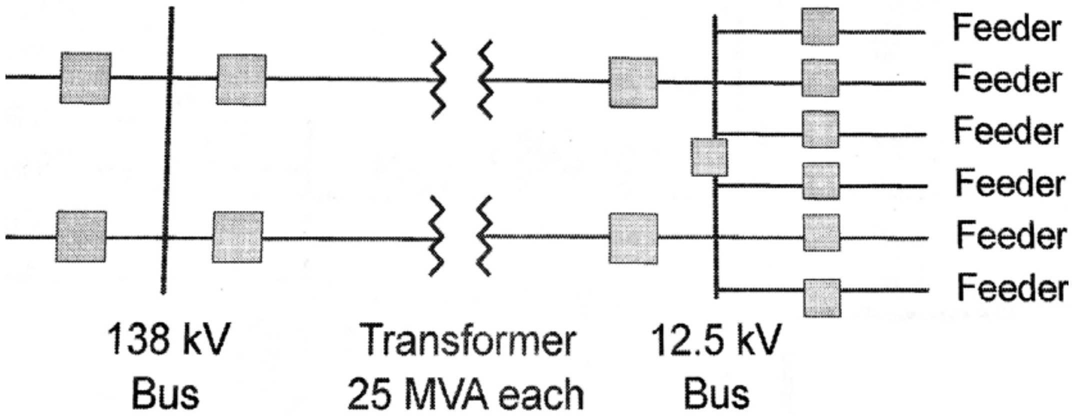


Figure B7 - One-Line example of a 138kV to Distribution Step-Down Substation (University of Wisconsin-Madison 2014)

Power Transformer (XFRM)

A power transformer (XFRM) is a 3-phase electrical component that uses various windings to change (step-down or step-up) the voltage from one level to another, such as going from 138kV to 69kV. (USDA 2001) Figure B8 below shows a typical XFRM that might commonly be seen inside a substation facility. As seen in Figure B8 below, XFRMs are typically one of the largest pieces of equipment within the substation site and sit on a large concrete foundation pad. They contain large fans for cooling and dissipating heat, and have large tanks for oil to be used as a cooling mechanism as well. (USDA) Along with this, the XFRM has an oil containment system (typical sunken foundation with metal grate on top) for mitigating environmental impacts due to potential oil spill.

Figure B8 - Example of a High-voltage Power Transformer (Newhart Services 2015)

Production (Productivity)

Productivity, or production, is generally defined within the construction industry as the output of work per a measured amount of labor hours. (Shehata 2012) It can also be seen or known in the industry as a unit rate, where labor hours are described per unit of installation (Labor hours/ Units). (Shehata 2012)

Step-down Substation (Change in Voltage Substation)

Step-down substation is also commonly known as a change in voltage substation. These facilities are very common in high-voltage (69-345kV) transmission applications. The primary function of these facilities is to change the voltage along the transmission line path from one voltage level, such as higher voltage of 345kV on the primary side, down to 138kV level on the secondary side via a 3-phase power transformer. Figure B9 below illustrates this configuration in a plan view form with the power transformer dropping the voltage down from 345kV to 138kV.

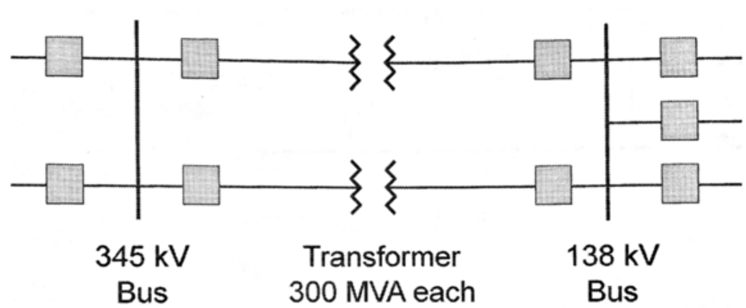


Figure B9 - One-Line example of a 345 to 138kV Step-Down Substation (University of Wisconsin-Madison 2014)

Support Steel (Steel Stand and Lattice Steel Structures)

Steel structure types are primarily used within the substation facility to hold up electrical equipment. Other materials can be used, but steel is typically the most commonly used. There are several design functions that the steel supports provide. First, it it provides overall structure support to withstand appropriate structural loads (wind, ice, etc). Second, structural steel supports are used to provide clearances from the equipment to the ground or other objects. Also, steel can be galvanized which prevents corrosion and longer lifespan. (University of Wisconsin-Madison 2014) A few examples of the different structural steel types used within a substation facility are shown below. Figure B10 shows common steel support stands for a rigid bus design. The steel supports shown in the picture are used to hold up the rigid bus (circled in Figure B10). Figure B11 below also shows stands being used tp hold up smaller equipment items such as disconnect switches (circled in the figure) or other components. (USDA 2001)

Figure B10 - Equipment Steel Support (TESCO 2013)

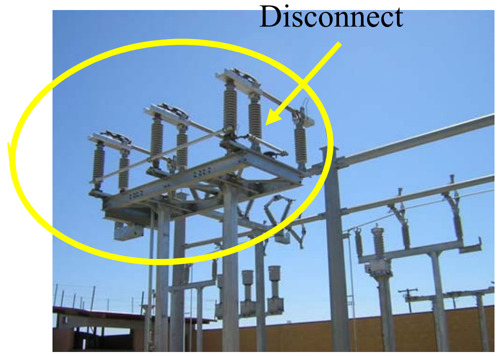


Figure B11 - Steel Support Structures for Disconnect Switch (LGE Electrical Sales 2015)

Along with the items mentioned above, it is also common in substation facilities to have steel lattice box structures and steel dead-end structures. Figure B12 below illustrates a typical steel lattice box structure. The lattice box is composed of angled steel sections, with beams and columns made up of those components. (USDA 2001) Steel box structures are typically used for ring bus configurations due to their advantage of providing a more compact design, structural capability, and allow several line terminals. (USDA 2001) They also can be preassembled from the manufacturer to reduce construction erection time in the field. (USDA 2001)

Figure B12 - Steel Lattice Structure for Ring Bus Configuration (Heinemann et al. 2012)

As discussed above, steel structures are also used for line terminal structure applications. (University of Wisconsin-Madison 2014) Line terminal structures are used to support the incoming transmission line into the substation facility, and to dead-end the phase conductors and shield wires onto the structure before entering the substation. (USDA 2001) For this reason, these structures typically require a significant amount of design effort due to the extreme transmission loading that they need to be able to handle. (USDA 2001) Figures B13 below shows a typical example of dead-end structure applications. These are commonly known and can be identified in the field as "H-frame" or "A-frame" structures due to their geometric shapes.

Figure B13 - Steel Dead-end "H- frame" (Pacific Steel Structures 2009)

Transmission Switchyard Substation (Switching Substation)

These facilities are very common in high-voltage (69-345kV) transmission applications. They do not contain a power transformer to change or step-down the voltage, and consist solely of transmission line terminals with circuit breakers and buswork. Therefore, their primary function is to provide grid flexibility, change or switch of the power for outages, maintenance work, or isolation of faults. (USDA 2001) Figure B14 below illustrates this configuration in a plan view form with power flow control via high-voltage circuit breakers between the transmission line terminals.

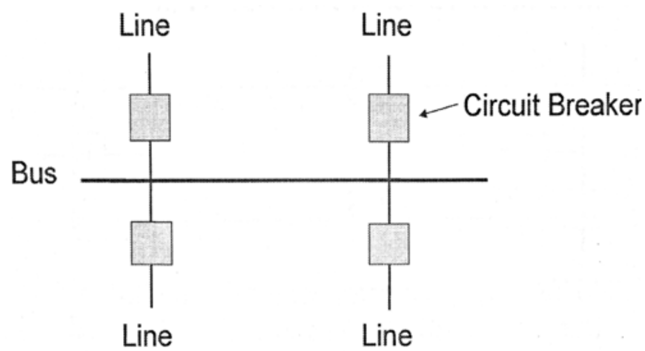


Figure B14 - One-Line example of a Transmission Switchyard Facility
(University of Wisconsin-Madison 2014)

Work Breakdown Structure (WBS)

The Work Breakdown Structure (WBS) is a best practice that details out the work elements of the project and helps break down the project into manageable components at various activity levels. (AACE 2011) The WBS also establishes a visual hierarchical summary of the work in which "the schedule, cost, and project controls will be based on."(Hyde et al. 2010) A general outline for a WBS is illustrated in Figure B15 below. The research conducted for substation projects will later illustrate a WBS example. This example will provide a typical starting point and can modified as needed depending on the scope of the substation project.

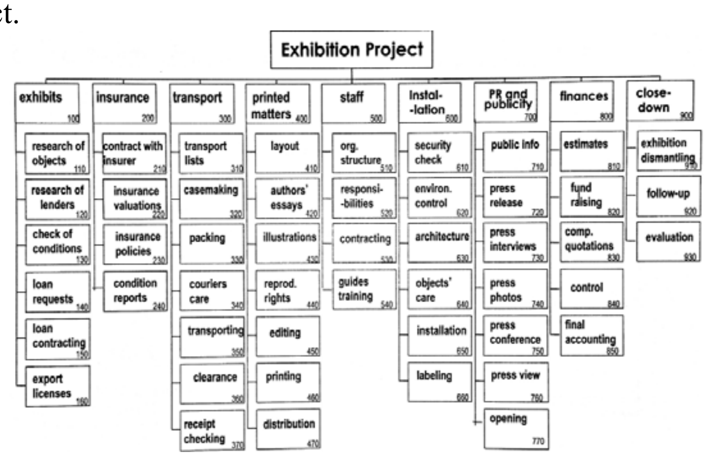


Figure B15 - WBS Example for a Project in Visual Hierarchical Structure
(University of Wisconsin – Madison 2012)

APPENDIX C. PROJECT SURVEY TEMPLATE (Microsoft Word File)

Substation Electrical Contractor Construction

- High-voltage Substation Projects for "Electrical Scope of Work".
- "Electrical" contractor scope of work defined as:
  - Not including grading, foundations, site work, and other below grade activities such as installing conduit and trenches.
  - Not including Transmission line scope for the project.

Instructions

This survey is for the Construction phase of the substation project only, starting at the end of below grade work (foundations and grading) and concluding with final construction in-service and commissioning. This therefore covers only the electrical scope of work for the project and doesn't include any below grade activities.

There are 7 sections in the survey, with the summary of each section bulleted below. The items noted with an "*" in the survey include additional information and description at the base of the survey. It is preferred that this survey form be filled out based on a "new large High-voltage Substation construction project" for projects considered good or better than average for you company. (High-voltage meaning >69kV, and large meaning > 8,000 labor hours, "good" project characterized within +10 -30 % labor hours). (Need to define "good" yet further"

1. General Information
2. Project Characteristics
3. Project Labor, Cost, and Schedule Data – Baseline and Actual Data
4. Project Change Order
5. Contract Document and Contract Type
6. Project Management: Resource Tracking and Physical Tracking
7. Construction Labor Crew Makeup

The intent of the survey is to be completed by the members of the project team that were managing the on-site construction. Questions should be answered to the best of your team's ability, with data provided to support results as noted in the survey. (Specifically labor hours over the life of the project for manpower information)

All data collected and provided for the survey that the team member and organizations provide is confidential. The data will not be viewed by any party other than those of the University of Wisconsin Construction Engineering and Management (CEM) Research staff members.

Should you have any questions with the survey, please contact Dr. Hanna via email (ahanna@wisc.edu) or by phone xxxxx.

The UW CEM Research staff members thanks you for your participation in this initiative to gather substation electrical construction data.

SECTION 1: GENERAL INFORMATION

Person completing this part of the survey:

Your Name:

Address:

Your Company Name:

Your Cumulative Years of Experience in Capital Projects:

Telephone Fax Email

Would you prefer correspondence by email or telephone (please circle one)?

What is the best time to reach you (indicate time zone)?

What position do you hold within your construction company?

- ☐ Owner
- ☐ President
- ☐ Vice president
- ☐ Superintendent
- ☐ Project manager
- ☐ Other (specify) ________

Owner Company Name:

Project Construction Location: City: _________, State: ______,

Project Location Type: Urban_____ Rural_____ Other_______

Lead Construction Contractor: Name: ____Contractor ____State:

SECTION 2: PROJECT CHARACTERISTICS

1. Project type:
   - ☐ Substation Change in Voltage (step up or step down voltage station)
   - ☐ Substation Switching Station

2. What type of construction was this project?
   - ☐ Addition or expansion
   - ☐ Grass Roots, Greenfield (New construction) (~80acres)
   - ☐ Brownfield (co-locate)
   - ☐ Renovation, Upgrade

3. What was the substation prime voltage?
   - ☐ 345 kV
   - ☐ 138 kV
   - ☐ 69 kV
   - ☐ Other (Please specify)

4. What was the substation secondary voltage?
   - ☐ 345 kV
   - ☐ 138 kV
   - ☐ 69 kV
   - ☐ Other (Please specify)

5. What was the main configuration of the substation?
   - ☐ Ring bus
   - ☐ Straight bus (345 kV)
   - ☐ Radial bus
   - ☐ Breaker and a half (138kV)
   - ☐ Other (Please specify)

Notes:

6. What was the main bus type used?
   - ☐ Rigid Tubular steel
   - ☐ Strain bus
   - ☐ Lattice box structure
   - ☐ Other (Please specify)

7. How many terminals/bays (line designations) did this substation have INSTALLED?

___ Quantity of terminal bays (line designations) installed

8. How many terminals/bays (line designations) did this substation have designed total for FUTURE?
____ Quantity of terminal bays (line designations) future

9. How many large voltage step-up/step-down transformers did this substation have?
___ Quantity of large voltage transformers

☐ None, this was a switching station
☐ Other (Please specify)

10. How many circuit breakers did this project have?
___ Quantity of breakers

11. Was any part of your project executed on an existing operating unit/brownfield site?
☐ Yes X No
If yes, was this Partial site or Majority of Site?
☐ Partial ☐ Majority

12. How many OSHA recordable occurred on this project?

☐ 0 ☐ 1-3 ☐ 3-6 ☐ 6+

SECTION 3: PROJECT LABOR, COST, AND SCHEDULE DATA

1. The contract budgeted crew labor hours[7] at the notice to proceed for the project:
(Note this is for "electrical installation scope only": installing steel supports/structures, setting equipment, setting control house, wiring, terminations, grounding, installing above-grade conduit. Not including any below grade work of trenching for conduit, installation of duct banks, installing conduit in trenway/ducts, civil work of foundations, grading, and any removals hours and any PMO or superintendent/GF costs. Direct crew labor hours only, those procuring the work no oversight)

Direct electrical scope baseline labor hours _________ hrs.

* Please provide example of construction estimate if available.

2. The actual labor hours utilized at completion of the project, including change orders:

[7] Contract budgeted labor hours – The total estimated labor hours (man-hours) that the contractor used to allocate labor resources.

(Note this is for "electrical scope only": installing steel supports/structures, setting equipment, setting control house, wiring control house, etc., not including below grade work of conduit install/trenway/ducts, foundations)

Actual electrical scope direct labor hour's _____________hrs.

- Please provide example of budget vs. actual that was used for this data if available

3. The estimated planned project duration at contract award for electrical scope: (From electrical start (Setting Steel Structures Start, receive and assemble transformers, or setting control house if new house set first) to construction completion of electrical scope
__planned construction calendar weeks
__ planned electrical construction start
__ planned electrical construction finish (construction of electrical scope complete)

4. The actual project duration at completion for electrical scope: (From electrical start (Setting Steel Structures Start, receive and assemble transformers, or setting control house if new house set first) to construction completion of electrical scope)

____ Actual construction calendar weeks
____ Actual construction start
____ Actual construction finish (in service date)

5. The estimated project construction cost for electrical work: (Labor and Equipment Only (L&E))
__________ Estimate electrical scope L&E construction
*Note, please provide cost data sheet or example of estimate if available
Excluding foundation, site work, grading (below grade scope)

6. The actual electrical project L&E construction cost: (Labor and Equipment Only)
______ Actual electrical scope L&E construction $ (excluding foundation, site work, grading (below grade scope))

*Note, please provide cost data sheet of budget/actual if available

SECTION 4. PROJECT CHANGE ORDER SECTION

1. The total submitted requested change order labor hours for electrical scope of work? (Requests documenting the changes but not approval yet to the Purchase Order)

Direct labor hours requested for changes __________________hrs.

2. The total owner[4] approved change order labor hours for electrical scope of work (these are change order hrs. that are approved and increase or decrease the Purchase Order once approved)

Direct labor hours for changes approved by owner __________________hrs.

* Notes: any special notes as to if these were actual change orders or Change Requests

3. The total credit change order hours requested, if any (i.e., for deletions of electrical scope):

Direct labor credit hours ________________hrs.
Total credit hours ______________hrs.

4. The total credit change order hours approved by owner and changes made to Purchase Order, if any (i.e., for deletions of electrical scope):

Direct labor credit hours ________________hrs.
Total credit hours ______________hrs.

5. The actual electrical project construction change order costs requested and submitted to owner? (Excluding major equipment purchased)

___ Actual construction change order $ requested
*Note, please provide cost data sheet of budget/actual if available

6. The actual electrical project construction change order costs approved and changes to Purchase Order? (Excluding major equipment purchased)

___ Actual construction change order $ approved to Purchase Order
*Note, please provide cost data sheet of budget/actual if available

7. for the following five stages of the project's duration, please indicate the percentage of the project's change orders that were executed during each interval (in your best opinion).

Percent of Project Complete	**Percentage of Change Order Labor hours Executed**
• Before construction	_______%_____
• 0 - 25% of total labor hours	______%
• 25 - 50% of total labor hours	______%
• 50 - 75% of total labor hours	______%
• 75 - 100% of total labor hours	______%

- (Total percentages should sum to 100 %.)

8. Number of owner initiated change items:

______ #

9. Number of contractor initiated change items:

______ #

11. Number of change items requested:

______ #

12. Number of change items approved for PO Change by Owner:

______#

13. The following are possible reasons for change orders. For each reason that applies to your project, indicate the percent of actual executed labor hours of change orders.

SECTION 5: CONTRACT DOCUMENT AND CONTRACT TYPE

1. Contract type for this project:
   - ☐ Lump sum
   - ☐ Reimbursable cost plus fee
   - ☐ % fee
   - ☐ Fixed fee

   1a. was a guaranteed maximum price used on this project?
   - ☐ Yes
   - ☐ No
   - ☐ Unit price
   - ☐ Other (specify) ___

2. Was there a fixed end date for this project?

   ☐ Yes ☐ No

   If answer to question 3 is yes, describe why the fixed end date was necessary (time was of the essence)?____
   ____
   ____
   ____

3. The project delivery approach for this project:

☐ Design-bid-build "hard money" (Defined as sequence of design and construction phases, owner contracts separately with engineer and contractor)

☐ Design Assist (Contractor provides input during the engineering and design stage but does not do design.)

- ☐ Design-build (Owner contracts with the Design-build contractor directly)
- ☐ Design-build/engineer/procure/construct (EPC)

  Was a joint venture formed between the design firm and the constructor?
  - ☐ Yes
  - ☐ No

☐ CM at Risk (Owner contracts with engineer and construction manager (CM) who holds the contracts.

- ☐ Other (specify) ___________________________________

SECTION 6: CONTRACTOR'S PROJECT MANAGEMENT: SCHEDULING, MANPOWER, AND TRACKING

1. Was Critical Path Methodology (CPM) used for scheduling, and if yes, what software package was used? Please provide an example of the final schedule with actual and baseline dates. ____________

2. Did you make an estimated manpower loading graph for the project? (If so, please provide data in tabular format. This can be just columns with labor hrs. Per week individual or cumulative, see attached excel sheet for filling in hrs.)

☐ Yes ☐ No

(Note: insert place to upload document in survey here or provide to survey contact via email)

3. Did you update the manpower loading graph for the project based on actual labor hours and new estimates?

☐ Yes ☐ No

If yes, how often was the manpower loading graph updated? __________

Note: Please attach estimated and actual manpower loading graphs or weekly manpower data in excel or table data from the project records. Note, weekly tracking sheets with hrs. can also be provided and research team will compile curves if that is easier.

4. The peak number of FTE* planned and used for the project:

a. ~ # Peak FTE Planned **

b. ~ # Peak FTE Actual **

5. The average number of FTE used for the project:

a. ~ # Avg FTE Planned **

b. ~ # Avg FTE Actual **

*(FTE defined as = full time equivalents, based on 50hr work week)

**Note, this information can be gathered from a planned vs. actual manpower loading curve if that is provided instead as requested in Section III.

6. Did you track actual installed quantities?

☐ Yes ☐ No

7. What primary method of actual percent complete was primarily used for physical electrical construction scope?

☐ Subjective ☐ 0-50-100% ☐ 0-100% ☐ Actual units measured

8. Did you track performance productivity (input [labor hours]/output [units installed]) for the project?

☐ Yes ☐ No

SECTION 7: CONSTRUCTION LABOR AND CREW MAKEUP

1. What were the approximate Apprentice to Journeyman crew makeup ratios? (observe time sheet data for this)

   ☐ 0-25% ☐ 30-65% ☐ 75-100%

2. Was a General Forman used on the project? ☐ Yes ☐ No (Check percentage utilized below)

   ☐ 0-25% ☐ 30-65% ☐ 75-100%

3. Was a Superintendent used on the project? ☐ Yes ☐ No (Check percentage utilized below)

   ☐ 0-25% ☐ 30-65% ☐ 75-100%

4. What was the typical foreman to craft ratio used on the project: (actual observed or typical for project calculated as ratio = foreman hrs. /total electrical crew hrs.)

   ☐ <5:1 ☐ 6:1 ~ 8:1 ☐ 9:1 ~ 12:1 ☐ >13:1

   Specific Notes:

APPENDIX D. RESEARCH TEMPLATE FOR EXCEL DATA INPUT

Data Project X, Company X								Primary Above Grade Electrical Activities by Chategory					
								AG Grounding	AG Conduit	Control Cable Hrs	Steel	Major Equipment	Bus and Hardware
Project % Duration Complete	Week #	Week Ending Date	Above Grade Electrical Scope Cummulative hrs for major electrical tasks(hrs from begin AG or steel set to substantial completion)	% actual manhours (cummulative)	Weekly Hrs	Cummulative FTEs	Weekly FTEs	Above Grade Grounding and Fence Grounding	Above Grade Conduit and J-box	Control/Power Cable Hrs	Support Steel Hrs (Bus Supports, Des, Static Masts)	Major Equipment Install Hrs (CB, XFR, Disconnects)	Bus (strain and static and rigid) and Hardware HRs
Baseline	Baseline	Baseline	0	0%	0	0	0						
0%	0		0	0%	0								
3%	1		0	0%	0	0							
7%	2		0	0%	0	0							
10%	3		0	0%	0	0							
14%	4		0	0%	0	0	0						
17%	5		0	0%	0	0							
21%	6		0	0%	0	0							
24%	7		0	0%	0	0							
28%	8		0	0%	0	0	0						
31%	9		0	0%	0	0	0						
34%	10		0	0%	0	0	0						
38%	11		0	0%	0	0	0						
41%	12		0	0%	0	0	0						
45%	13		0	0%	0	0	0						
48%	14		0	0%	0	0	0						
52%	15		0	0%	0	0	0						
55%	16		0	0%	0	0	0						
59%	17		0	0%	0	0	0						
62%	18		0	0%	0	0	0						
66%	19		0	0%	0	0	0						
69%	20		0	0%	0	0	0						
72%	21		0	0%	0	0	0						
76%	22		0	0%	0	0	0						
79%	23		0	0%	0	0	0						
83%	24		0	0%	0	0	0						
86%	25		0	0%	0	0	0						
90%	26		0	0%	0	0	0						
93%	27		0	0%	0	0	0						
97%	28		0	0%	0	0	0						
100%	29		0	0%	0	0	0						
						Max Peak							
						Peak %							
						Average							

APPENDIX E. SUMMARY OF EXCEL DATA – PROJECT CHARACTERISTICS

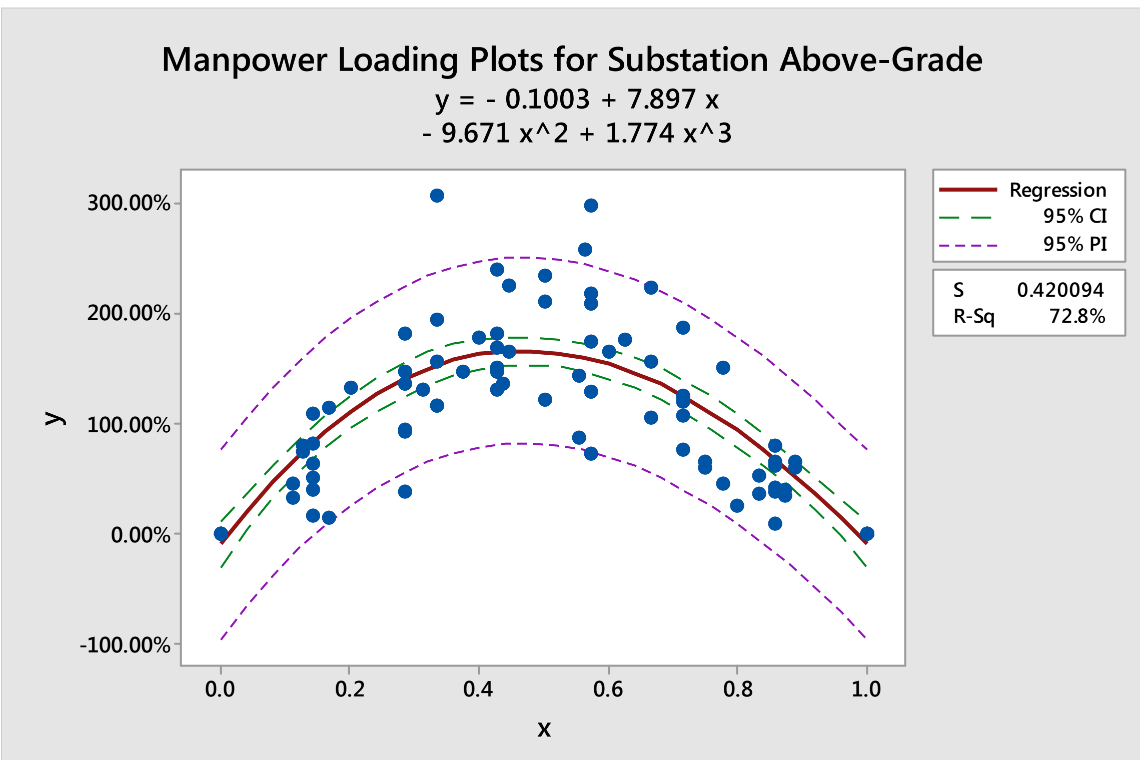
Location	Project Type	New, Addition or expansion	Primary Voltage
Rural	Change in Voltage	Grass Roots (new)	345 kV
Rural	Substation Switching	Grass Roots (new)	138 kV
Rural	Change in Voltage	Addition or expansion	138 kV
Urban	Substation Switching	Addition or expansion	345 kV
Rural	Change in Voltage	Grass Roots (new)	138 kV
Urban	Substation Switching	Addition or expansion	138 kV
Rural	Substation Switching	Grass Roots (new)	69 kV
Rural	Change in Voltage	Addition or expansion	345 kV
Rural	Change in Voltage	Grass Roots (new)	138 kV
Rural	Change in Voltage	Grass Roots (new)	138 kV
Rural	Change in Voltage	Grass Roots (new)	138 kV
Rural	Change in Voltage	Addition or expansion	138 kV
Rural	Change in Voltage	Addition or expansion	138 kV
Rural	Substation Switching	Grass Roots (new)	345 kV

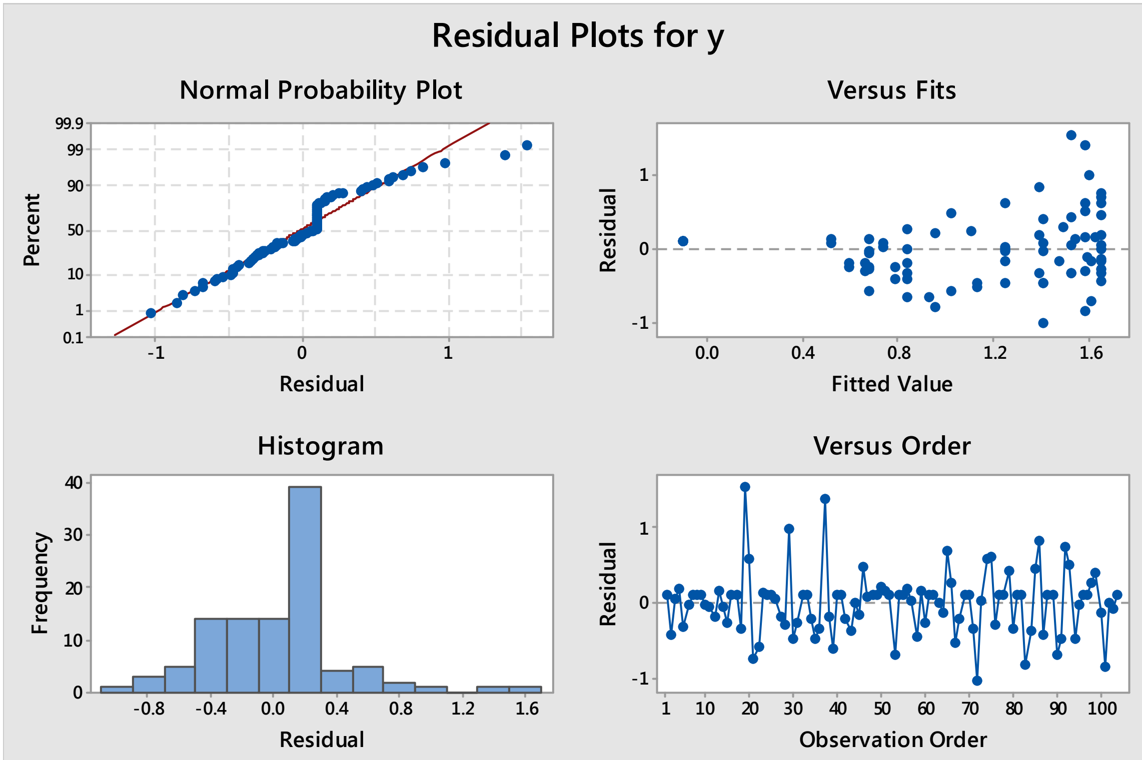
APPENDIX F. MINITAB© RESULTS

Appendix F1. Manpower Loading Curve Minitab© Analysis and Report

Polynomial Regression Analysis: y versus x

```
The regression equation is
y = - 0.1003 + 7.897 x - 9.671 x^2 + 1.774 x^3


S = 0.420094   R-Sq = 72.8%


Analysis of Variance

Source        DF       SS       MS      F      P
Regression     3  47.2328  15.7443  89.21  0.000
Error        100  17.6479   0.1765
Total        103  64.8808


Sequential Analysis of Variance

Source     DF       SS       F      P
Linear      1   0.1150    0.18  0.671
Quadratic   1  46.9153  265.45  0.000
Cubic       1   0.2025    1.15  0.287
```



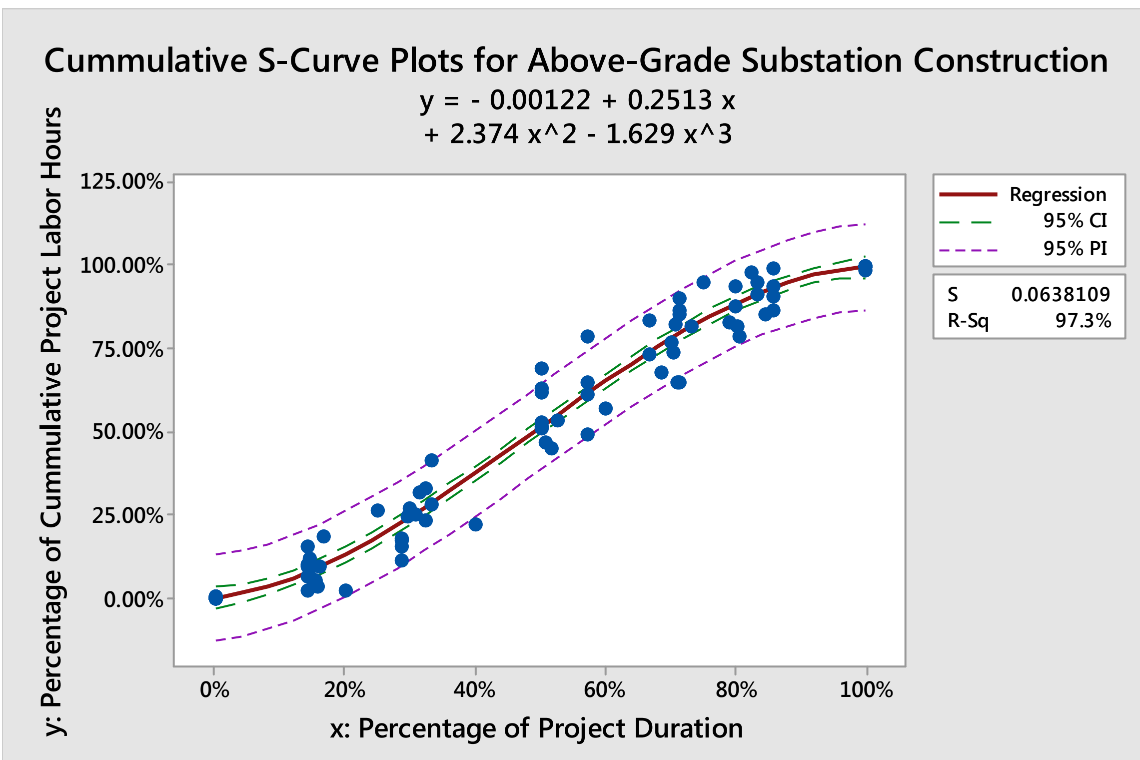


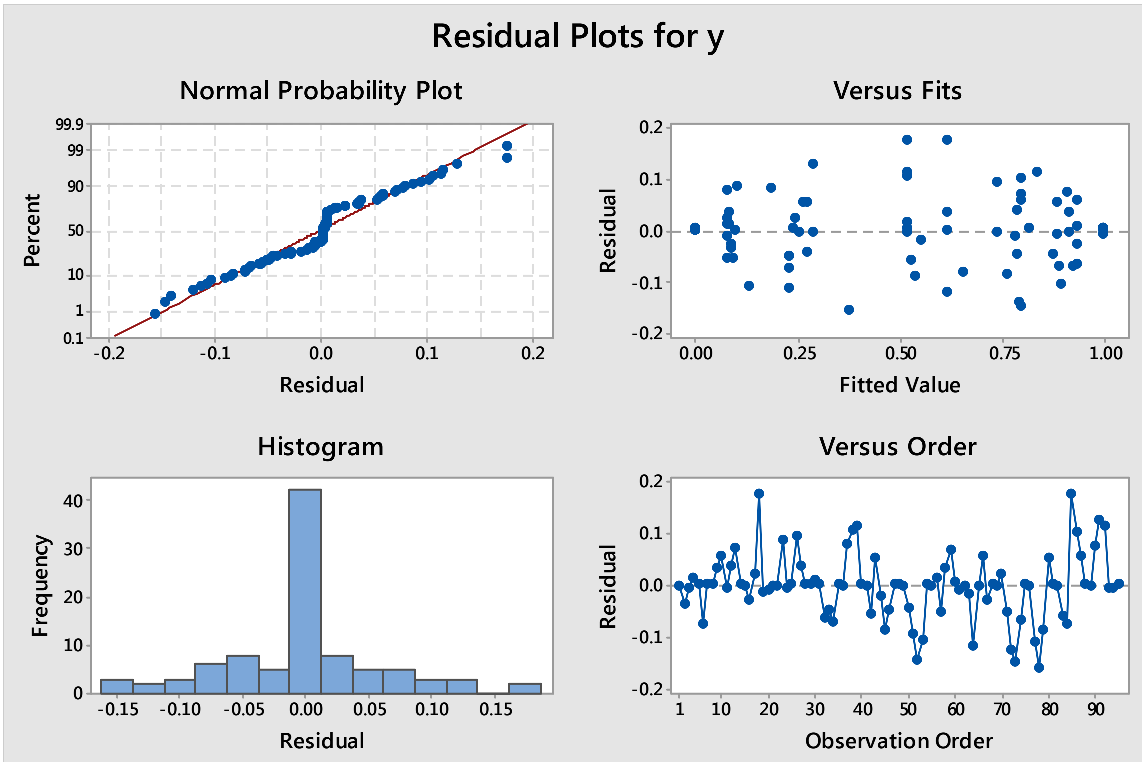
Residual Plots for y
Normal Probability Plot
Percent
99.9
99
90
50
10
1
0.1
-1
0
1
Residual
Versus Fits
Residual
1
0
-1
0.0
0.4
0.8
1.2
1.6
Fitted Value
Histogram
Frequency
40
30
20
10
0
-0.8
-0.4
0.0
0.4
0.8
1.2
1.6
Residual
Versus Order
Residual
1
0
-1
1
10
20
30
40
50
60
70
80
90
100
Observation Order

Appendix F2. S-Curve Minitab© Analysis and Reports

Minitab© Results

```
The regression equation is
y = - 0.00122 + 0.2513 x + 2.374 x^2 - 1.629 x^3


S = 0.0638109   R-Sq = 97.3%


Analysis of Variance

Source      DF       SS       MS        F      P
Regression   3  13.3365  4.44549  1091.77  0.000
Error       91   0.3705  0.00407
Total       94  13.7070


Sequential Analysis of Variance

Source     DF       SS        F      P
Linear      1  13.1538  2211.38  0.000
Quadratic   1   0.0070     1.18  0.281
Cubic       1   0.1757    43.14  0.000
```





Residual Plots for y
Normal Probability Plot
Percent
99.9
99
90
50
10
1
0.1
-0.2
-0.1
0.0
0.1
0.2
Residual
Versus Fits
Residual
0.2
0.1
0.0
-0.1
-0.2
0.00
0.25
0.50
0.75
1.00
Fitted Value
Histogram
Frequency
40
30
20
10
0
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
Residual
Versus Order
Residual
0.2
0.1
0.0
-0.1
-0.2
1
10
20
30
40
50
60
70
80
90
Observation Order

APPENDIX G. REPORTING TOOL EXAMPLES

Appendix G1. Substation Timesheet Example

Daily Report - SS Timesheet Tracking Example

Date: Sample			WO#: Sample															
Crew Foreman: Research Team Sample			Project Desciption: SS Research Sample															
Employee Information			Production Codes & Hrs Worked - List Cost Code with Hrs (see codes below)															
			EX: 1000		EX: 2100													
Name of Employee	Employee #	Class	ST	OT	ST	OT	ST	OT	ST	OT	ST	OT	ST	OT	ST	OT	ST	OT
Sample Person	1111	Apprentice		2	8													

Production Units Completed for Date XX

Description, WBS activity, and Accounting Code					
Desciption	WBS #	Cost Code	Unit of Measure	Units Completed	Description of Work Completed (Location, Qty, etc)
Grounding	1.0	1000	LF	30	Installed 3-10' tails of grounding for steel cirbuit breakers at position 3
Conduit	2.1	2100	LF	50	Installed 50' of conduit. 30' at CB position 3 and 20' up steel support X
Junction Box	2.2	2200	EA		
Dead End Tower	3.1	3100	EA		
Bus Support	3.2	3200	EA		
Static Mast	3.3	3300	LF		
Pull Cable	4.1	4100	LF		
Cable Terminations	4.2	4200	EA		
Circuit Breaker	5.1	5100	EA		
Disconnect Switches	5.2	5200	EA		
Transformer	5.3	5300	EA		
Misc. Equipment	5.4	5400	EA		
A-Frames (set of 3)	6.1.1	6110	Set		
Tubular Bus (rigid)	6.1.2	6120	EA		
Jumpers (per phase)	6.2.1	6210	EA		
Strain Bus	6.2.2	6220	LF		
Static Conductor (shielding)	6.2.3	6230	LF		
Insulators (set of 3)	6.3	6300	Set		

Appendix G2. Substation Production Tracking Sheet Example

SS Productivity Tracking Sheet (Units Completed and Planned Units Example Sheet)											
Description, WBS activity, and Accounting Code			Unit of Measure	Total Baseline Units Planned	Total Actual Units to Date	Week 1		Week 2		Week 3	
Description	WBS #	Cost Code				Planned	Actual	Planned	Actual	Planned	Actual
Grounding	1.0	1000	LF								
Conduit	2.1	2100	LF								
Junction Box	2.2	2200	EA								
Dead End Tower	3.1	3100	EA								
Bus Support	3.2	3200	EA								
Static Mast	3.3	3300	LF								
Pull Cable	4.1	4100	LF								
Cable Terminations	4.2	4200	EA								
Circuit Breaker	5.1	5100	EA								
Disconnect Switches	5.2	5200	EA								
Transformer	5.3	5300	EA								
Misc. Equipment	5.4	5400	EA								
A-Frames (set of 3)	6.1.1	6110	Set								
Tubular Bus (rigid)	6.1.2	6120	EA								
Jumpers (per phase)	6.2.1	6210	EA								
Strain Bus	6.2.2	6220	LF								
Static Conductor (shielding)	6.2.3	6230	LF								
Insulators (set of 3)	6.3	6300	Set								

Appendix G3. Substation Progress Reporting Example

[A]	[B]	[C]	[D]	[E]	[F]	[G]	[H]	[I]	[J]	[K]	[L]	[M]
SS Above Grade Scope WBS			Budgeted Information		Labor Hours		Production Units		Performance			
WBS Higher Level	WBS Task	Activity/Task	Budgeted Hours	Budgeted Units	Actual Hours (To Date)	Percent Hours Complete (To Date)	Actual Units Completed (To Date)	Percent Units Complete (To Date)	Earned Hours	Activity Performance Factor	Baseline Unit Rates (Manhours/ Unit)	Actual Unit Rates (Manhours/Unit)
Grounding	1	Grounding	Estimate	Estimate [LF]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
2.0 Conduit	2.1	Conduit	Estimate	Estimate [LF]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	2.2	Junction Box	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
3.0 Steel	3.1	Dead End Tower	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	3.2	Bus Support	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	3.3	Static Mast	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
4.0 Cable	4.1	Pull Cable	Estimate	Estimate [LF]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	4.2	Cable Terminations	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
5.0 Major Equipment	5.1	Circuit Breaker	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	5.2	Disconnect Switches	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	5.3	Transformer	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	5.4	Misc. Equipment (PT,	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
6.0 Bus and Hardware	6.1.1	A-frames (Set of 3)	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	6.1.2	Tubular Bus Section (	Estimate	Estimate [LF]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	6.2.1	Jumpers	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	6.2.2	Strain Bus Conductor	Estimate	Estimate [LF]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	6.2.3	Static Conductor (Shi	Estimate	Estimate [LF]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
	6.3	Insulators (Set of 3)	Estimate	Estimate [EA]	∑ (timesheet)	[F] / [D]	∑(Field Measured)	[H] / [E]	[L]x[H]	[J] / [F]	[D] / [E]	[F] / [H]
Total Above Grade SS Scope			Estimate	Estimate [EA]	∑ (timesheet)	∑([F] / [D])	NA	∑ [J] / ∑ [E]	∑ [J]	∑ [J] / ∑ [F]		